SUPERHOT ROCK FOR SUSTAINABLE POWER GENERATION

Earth's deep heat, largely generated by the decay of naturally occurring radioactive isotopes distributed within the crust and mantle, has rich potential as a global geothermal resource, but we first need an accurate picture of where the heat is distributed

To exploit our deep geothermal resources, we need an accurate picture of where the heat is. Philip Ball, the team at Clean Air Task Force, and Juan Carlos Afonso explore new approaches for constraining the distribution of subsurface heat

IN THE CURRENT global geopolitical environment, many governments are looking towards alternative energy sources to assist with the phasing out of fossil fuels. Geothermal energy has seen an intensification of interest because it provides cost-competitive, low-carbon, always-available renewable energy, with a relatively small spatial footprint. Increased exploration is occurring in tandem with a boom in technological innovations, with an eye towards exploration of deeper and hotter geothermal resources.

A comprehensive understanding of subsurface temperatures and pressures is crucial to supercritical geothermal resource exploration. However, the scarcity of hard data to constrain subsurface models results in uncertainties in the global characterisation of thermal anomalies. Here we discuss the preliminary results from a research study in which we are using a 'bottom-up' approach to examine the predicted surface heat flow based on a lithospheric model and depths to critical isotherms – in this case, the 450°C isotherm. To tackle the location of deep heat, we explore uncertainties in the depth and spatial location of the thermal anomalies by comparing the 450°C isotherm to independent models, such as Curie depth point models, and by comparing the model-predicted surface heat flow to measurements. Here we see a first-order similarity, but there are important differences. The modelled results simplify the heat flow from the crust and mantle whereas the measured data may identify thermal signatures from hydrothermal activity, shallow and small-scale magmatic bodies and/or high conductivity rocks. When comparing the two (while acknowledging the data quality and limitations), we can try to characterise the first-order thermal structure of Earth's lithosphere and the geodynamic environments in which these anomalies occur, as we investigate the challenges of developing a superhot geothermal resource model.

Heterogenous heat

Earth's heat originates from various sources, including primordial heat generated during the planet's formation. However, the primary contributor to Earth's heat is the presence of naturally occurring radioactive isotopes such as Potassium 40, Uranium 238, Uranium 235, and Thorium 232, distributed within the crust and mantle. These elements are not evenly distributed, leading to heterogeneity in the mantle and crust. Generated heat is transferred in the crust and/or mantle through conduction, convection and advection. Locally, hydrothermal systems play a role in transferring heat from deep to shallow sections of Earth's crust through convection. At the larger 'plate tectonics' scale, mantle convection influences the distribution of heat in the mantle. In regions where plate boundaries form or mantle plumes and magmatic provinces emerge, convective and advective processes further modify local thermal conditions.

> “The primary contributor to Earth's heat is the presence of naturally occurring radioactive isotopes”

Historically, geothermal power plants primarily exploited hydrothermal and magmatic systems at shallow depths, around 2-3 km or < 5 km (with some exceptions). Consequently, most power plants were concentrated at divergent, convergent, or transcurrent plate margins (Uihlein, 2018). The biased distribution of hydrothermally derived geothermal power plants offers a limited understanding of heat flow in the shallow crust that is geographically constrained. Several regions have been drilled to temperatures greater than 350°C (www.catf.us/shrmap/). Of the 48 wells documented to have penetrated to such temperatures, 10 wells met both the pressure and temperature conditions required of supercritical reservoir conditions. These are located in Italy (Mofete 005, San Vito-1, Sasso-22, San Pompeo-2; ST1, ST2, Carboli-11, Quercenne-3; ST-1, Venelle-02, Latera-100), USA (Prati-32 re-drill), and Iceland (IDDP-1; ST1; ST2).

Enhanced or Engineered Geothermal Systems (EGS) have emerged as a solution to overcome the geographical limitations, decoupling the reliance on shallow hydrothermal systems. EGS typically involves drilling deep into dry, hot rocks, stimulating fractures in a synthetic reservoir, and circulating water through the system to generate steam or water. This approach enables exploitation of the hot and superhot rock resources that represent the deepest and highest →

temperature geothermal resource, and presents opportunities for decarbonising heating, cooling, electricity production, and industrial processes. Given that water enters the supercritical phase at 22 MPa (220 Bar) and 374°C (but increases with salinity), the transition to superhot geothermal opportunities involves drilling to depths greater than 5 km, where clean water enters the supercritical phase.

Our approach

Accurately calculating deep geotherms is challenging. To identify areas with potential superhot geothermal resources, we use a novel workflow that utilises a global lithospheric model to calculate the depth to the 450°C isotherm (Fig. 1).

The model, LithoRef18, is a 2ox2o global lithospheric reference model (Afonso et al., 2019) that was obtained through a formal joint inversion of 3-D gravity anomalies, geoid height, satellite-derived gravity gradients, and absolute elevation, complemented with additional seismic, thermal, and petrological information. One of the forward problems solved during the inversion is the steady-state, conductive heat transfer in the lithosphere. Importantly, surface heat flow is a prediction of the model rather than an input dataset; this allows for an independent validation of the model's predictions.

In continental lithosphere, we calculate the steady-state heat conduction using prescribed radiogenic heat productions and thermal conductivities that depend on the tectonic setting. In doing so, we subdivide the lithosphere into three layers: upper crust, lower crust, and lithospheric mantle. Each layer has its own set of thermophysical parameters (see Afonso et al., 2019 for details). For the continents, we find that the thermal gradient (and thus depth to the 450°C isotherm) is largely controlled by the lithospheric thickness and the assumed internal heat generation in the crust and sediments. For a seamless continent-ocean model, we also compute the lithospheric thermal structure for oceanic domains, using the plate model of Grose & Afonso (2013) based on the crustal ages from Müller et al. (2008). However, our focus here is on the continental domain.

Over the past five decades, understanding of Canada's geothermal resources has advanced significantly, so data from Canada are used to test preliminary models of heat flow. Shown here is the Bow River and Castle Mountain, Alberta, Canada.

> **“Significant advances in the understanding of Canada's geothermal potential have been made over the past five decades”**

The Canada case study

Globally, there are few well datasets that can be used to constrain temperatures at depth, and where they exist, they are biased to hydrothermal and magmatic systems. To examine the results of the modelling, we selected Canada as the focus of a preliminary study. Significant advances in the understanding of Canada's geothermal potential have been made over the past five decades (Jessop et al., 1991; Hickson et al., 2020), with studies exploring the thermal structure up to depths of 10 km (Grasby et al., 2009; 2012). Recent investigations also assess the possibility of accessing deep geothermal and supercritical heat to help decarbonise the Alberta oil sands business (Graham et al. 2022; Hirschmiller & Riva, 2022).

For the study we windowed the dataset over Canada to examine the predicted (modelled) surface heat flow (Fig. 2A) and the calculations of depth to the 450°C isotherm (Fig. 2B). In this quick analysis, we first used a comparison between our predicted surface heat flow (Fig. 2A) and measured surface heat flow (Fuchs et al., 2021) to create a residual map (Fig. 2C). Secondly, we compared our calculations of depth to the 450°C isotherm to available Curie depth point models, which are taken to represent the depth to the 580°C isotherm, with the assumption that the Curie depth point model should be deeper than our modelled 450°C isotherm (Fig. 2D). Thirdly, we looked at the spatial correlation between geothermal power plants (Uihlein, 2018), volcanoes (Ball et al. 2021; Garrity & Soller, 2009) and geological/tectonic domains (Hasterok et al., 2022; Fig. 2E). We focus on the approximate tectonic age, plotting the basement rocks by their last orogenic event.

Discrepancies and correlations

The residual surface heat flow map (Fig. 2C) reveals differences in the modelled and measured heat flow. The differences can be quite large, particularly in the west where it seems the LithoRef18 model may underrepresent the thermal structure. Conversely, in the areas where blues are observed, the model appears to predict higher surface heat flows. These anomalies require further investigation and lead us to question the quality of the surface measurements as well as the assumptions and data used in the model. Due to the coarse and regional nature of the model, it's possible that smaller-scale geothermal anomalies are hidden or missed in the modelled surface heat flow maps. It is also possible that the measured data contain historical errors. For example, regions with a surface heat flow of less than 25 mW/m^2 may represent the effects of shallow underground water flow, rather than being representative of the actual lithospheric geotherm. The regions with measured high heat flows may represent heat moved from deep to shallow depths via hydrothermal processes, rather than being representative of the deeper lithospheric geotherm. Differences may also be due to shallow magmatism linked to recent geodynamic events, or may reflect the fact the LithoRef18 model assumes average conductivities and does not account for lateral variability according to different rock types.

Further work is needed to investigate if the anomalies are real or simply errors in the model or measured data. Some of the dissimilarities between the maps may highlight the benefits of a bottom-up approach versus those gained from a top-down approach using only surface heat flow measurements, since heat flow in the lithosphere is not a linear process. The observed differences reinforce the importance of geologists knowing their 'thermal basement', including at a local level. That is, we need some idea of what the basement is in each area, as well as a ballpark estimate of the heat flow that is reasonable for the rock type and tectonic setting. Further work is needed to analyse and understand whether the differences are meaningful. For example, additional data constraining the radiogenic content of the sedimentary and basement rocks would help better calibrate the geological models.

Discrepancies between our calculations of the depth to the 450°C isotherm and the Curie depth point (assumed to represent the 580°C isotherm; Fig. 2D) are in some locations quite large – they ought not to be. Given the temperature difference is only 130°C, if a low geothermal gradient of 26°C/km is assumed, the bulk of our calculations for the 450°C isotherm should fall within the error of +/-5 km. The pink shades in figure 2D indicate regions where the 450°C isotherm is shallower than the 580°C isotherm (which it should be), but the difference in reported depth often exceeds +10 km. Blue shades highlight

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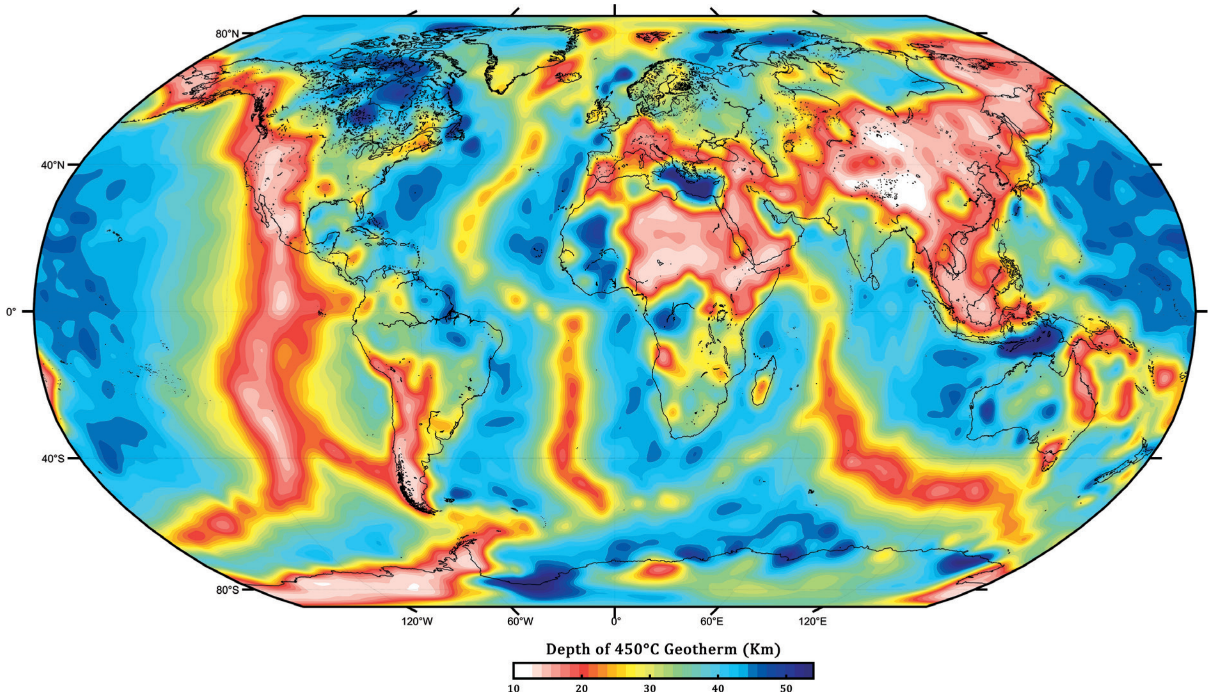

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Figure 1: Depth to the 450°C isotherm globally based on the LithoRef18 model (Afonso et al., 2019). Typical uncertainties associated with this depth are ~ 20%.

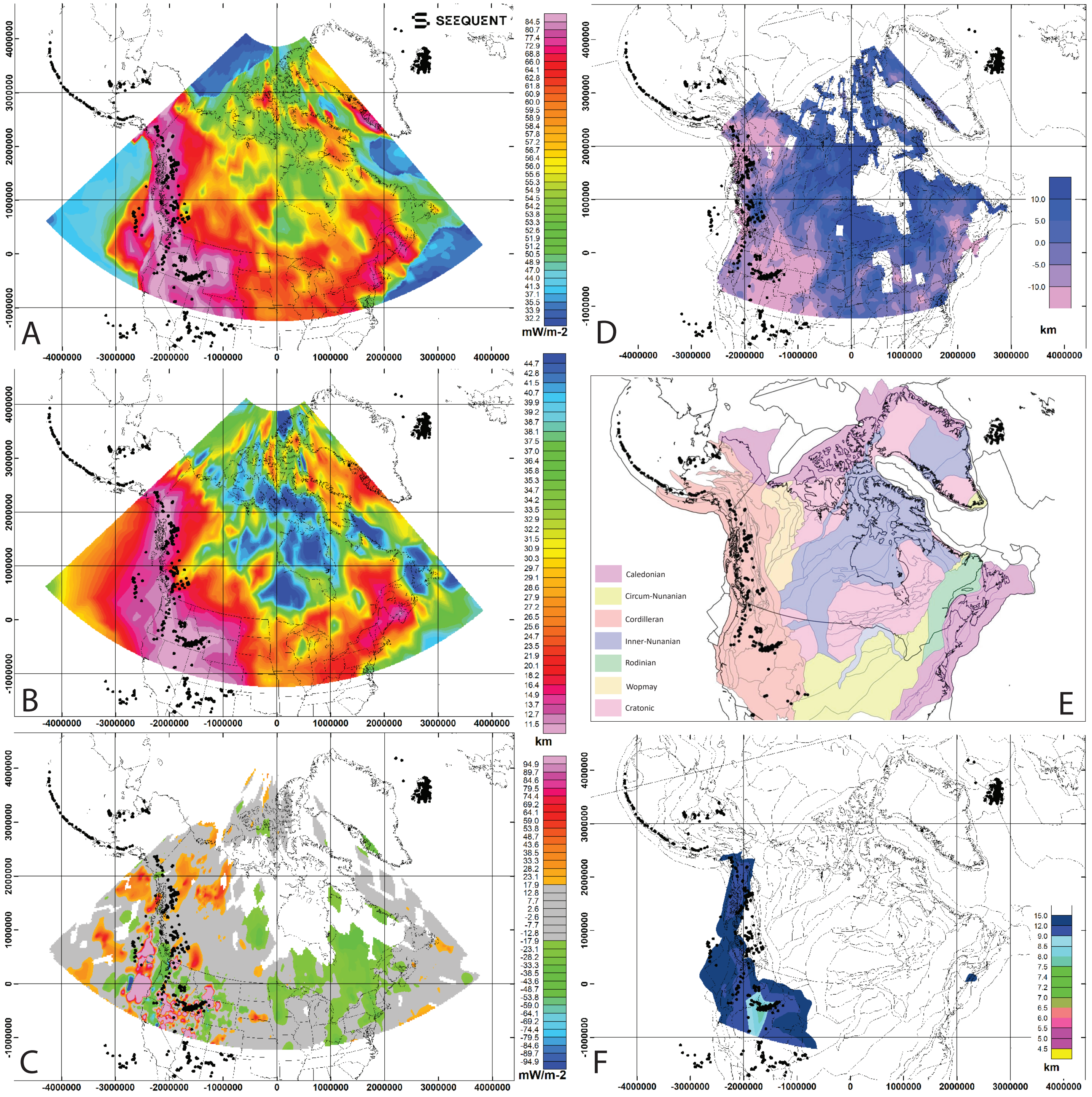

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Figure 2: Canada heat flow and isotherm modelling based on the LithoRef18 model (Afonso et al. 2019). (A) Predicted surface heat flow for Canada. (B) Predicted depth to the 450°C isotherm. Uncertainties associated with this map are ~ 20%. (C) Residual surface heat flow map. The difference between the measured surface heat flow (from Fuchs et al., 2021) and our calculations for surface heat flow. Here, pinks/reds indicate the measured surface heat flow model is hotter than the predicted LithoRef18 model and blues are where LithoRef18 model is hotter than the measured surface data. (D) Depth difference between the 450°C isotherm (calculated based on the LithoRef 18 model of Afonso et al. 2019) and the 580°C isotherm (based on the mean of the global Curie Depth Point models). Pinks mean the LithoRef18-calculated isotherm plots shallower than the Curie Depth Point interpretations. Blues indicate that the LithoRef18-calcuated isotherm plots deeper than the Curie Depth Point interpretations. Black lines are basement domains by last orogen age from Hasterok et al. (2022). (E) Basement domains by tectono-thermal age based on data from Hasterok et al., (2022). (F) LithoRef18 Model depth to 450°C. Black dots are known volcanoes from Ball et al. (2021) and Garrity & Soller (2009). For panels A,B,C,D & F, map scale ~1:50,000,000. NAD83/Canada Atlas Lambert.

regions where our calculations of the 450°C isotherm are deeper than the 580°C (which it should not be), and here we observe that the results can often exceed -10 km. Both models are affected by uncertainties and further work is needed to make a more informed assessment of these, as well as to clarify the reasons for the discrepancies.

By integrating knowledge of the basement (Fig. 2E), we observe that in general the 450°C isotherm plots deeper than the 580°C isotherm within cratonic areas and shallower in younger orogenic regions on the western and eastern margins of Canada. In cratonic regions with thick lithosphere, such as the Superior Province, Curie Depth Point models do tend to predict unrealistically shallow Curie depths, while our calculations of the 450°C isotherm depth based on the LithoRef18 model may underestimate subsurface temperatures given the relatively simplistic assumptions introduced in this model for radioactive heat production in continental crust. As discussed above, the observed correlations require further investigation, perhaps via the integration of available seismic reflection (such as LithoProbe) and refraction data, as well as integrated 2D gravity, magnetic and magnetotelluric modelling.

Despite the above discrepancies, our maps show clear positive correlations with volcanism and existing geothermal power plants, thereby supporting the potential predictive capabilities of our approach. The preliminary results discussed here represent a high-level investigation that reveals an underlying tectonic relationship in need of further exploration (Fig. 2F). For example, in the west we observe shallow 450°C-isotherm anomalies that correlate with the Cordilleran terrane (Hasterok et al., 2022), within the accretionary complex and volcanic arc basement types. In the east, shallow 450°C-isotherm anomalies occur in the Nova Scotian region – a Jurassic passive margin terrane, with an inherited Caledonian volcanic arc basement. It is possible that the eastern anomaly is related to overprinting tectonics linked to the breakup and formation of the Atlantic, but further work is needed to confirm this.

NEXT STEPS

We will apply 'Yet To Find' workflows (typical of the oil and gas sector) allowing us to turn our understanding of the location of shallow heat into estimates of potential TWth or TWe. By exploring the depth-to-heat scenarios, we can estimate what resources might be exploitable with today's available technology and also with incremental advances in drilling, electronics, well completions, reservoir management, and above-surface power plant technologies.

Future estimates will benefit from research that explores joint convection-conduction modelling in the global inversions – work that will begin as part of a newly formed Marie Sklodowska-Curie Doctoral Network, titled EarthSafe: Unveiling Earth's Critical Resources for Clean Energy and a Sustainable Future, led by the University of Twente, The Netherlands.

Informing stakeholders

Understanding the depth to heat and the spatial distribution of deep thermal anomalies is essential for the successful characterisation and exploitation of deep geothermal resources. But this is notoriously hard to do in the absence of constraining data.

Our analyses highlight that all representations of the subsurface have limitations. It is essential to remember that models are just models – not hard data. They carry a tremendous number of assumptions and while models are useful for identifying first-order patterns and relationships, they should be used with caution and awareness of their limitations.

Despite the limitations, our results can help inform geothermal stakeholders regarding potential deep geothermal resources globally. With improved understanding of these resources and how to exploit them responsibly, we can make significant progress towards a sustainable and greener energy future. G

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PHILIP BALL
Philip Ball, Chief of Geothermal Innovation in the Superhot Rock Energy team of the Clean Air Task Force (CATF)

JUAN CARLOS AFONSO
Juan Carlos Afonso, University of Twente, The Netherlands

FURTHER READING

A full list of further reading is available at geoscientist.online.

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