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Predicting the depth to geothermal reservoirs in Canada: Geothermal gradients and uncertainty analysis

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Summary

Predicting the depth to economic temperatures for geothermal reservoirs is the holy grail for geothermal developers. Temperature prediction at depth is imperfect, in part due to a limited data with inconsistent spatial coverage. In petroleum provinces there may be many thousands of wells drilled to a vertical depth of 2 to 3 km. However, the temperatures reported from these wells may not be in the enthalpy range needed for geothermal power generation. Large areas of Canada, therefore, may have an insufficient number of well-constrained temperature measurements of the subsurface. It is possible to use surface temperature/heat flow models, but there is not a linear relationship with depth for subsurface temperature prediction. Lithospheric models can be constructed, and statistical approaches or machine learning can be applied, to make predictions on the temperature. To date, these models lack resolution and high-quality datasets required to constrain temperature predictions in the 3-12 km range. Curie depth models can, in theory, indicate the depth to the 580ºC isotherm, but remain prone to error. The most reliable method to map the geothermal gradient is with accurate and quality controlled wellbore temperature measurements, but this is costly and time consuming.

In this paper we demonstrate a methodology and its implementation where, at any location in Canada, we combine multiple sources of data and 17 quantitative thermal models to estimate geothermal gradients and the depth to the desired economic temperature. We use mathematical models to connect the measured and modelled data points spatially (Kriging, IDW) and for any given location, via gradient and pressure profiles (non-linear regression model).

The predictions are accompanied by an uncertainty range derived from quantified P90 (adverse) and P10 (optimistic) scenarios allowing us to map and analyze the uncertainty in our depth to temperature assessments. The uncertainty range is needed as a non-deterministic input into chance-of-geological-success and prospect risk (opportunity and threat) forecasts in pre-drill geothermal projects. This uncertainty analysis also allows us to state our current confidence in our predictions and, more importantly, to ascertain which future information would narrow our uncertainty range and consequent risk range for the project.

Finally, we use the understanding gained from our geothermal screening to calculate the hydrostatic and lithostatic pressure.

The resulting library of data layers allows us to:

- Model geothermal gradients and their uncertainty at any location in Canada, and identify areas of interest for:
    - Projects with naturally flowing hydrothermal reservoirs, i.e. 'Mount Meager style' and 'Alberta Number 1-style'.
    - Reservoirs that may require an open loop, engineered heat exchanger, i.e. 'DEEP style'.
    - Reservoirs that may require a closed loop, engineered heat exchanger, i.e. 'EAVOR style'.
- Derive the pressure and depth of temperature targets that can be drilled with today's technology.
- Comment on which technological innovations would be needed to explore successfully for targets such as Superhot Rock petrothermal plays within Canada.

Theory

Recently, Graham et al. (2022) argued that 90% of the geothermal opportunity in Canada can be unlocked by using deep open loop, engineered technologies at depths of greater than 5 km. Presently there are very few hard-data points in Canada at these depths to provide any geothermal data. In addition, there are many uncertainties, for example the lithology, pressure conditions, stress regime, natural fracture network, and the "frackability" of the reservoir rock.

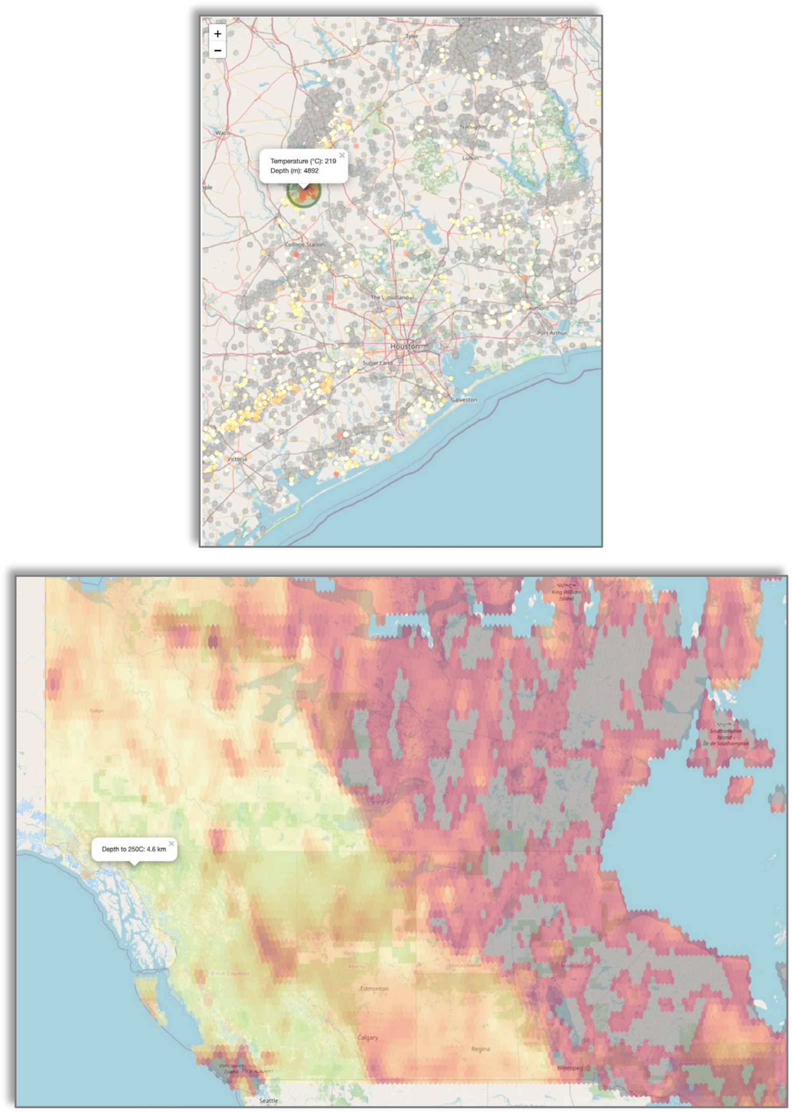
Significant efforts in recent years have improved knowledge of the thermal structure of selected regions of the Canadian subsurface (e.g. Jones & Majorowicz, 1988; Bachu & Burwash, 1991, Jessop et al., 1991; Grasby et al., 2009; Grasby et al., 2012; Majorowicz et al., 2014; Hickson et al. 2020; Sellers et al., 2023; Ball et al., 2025). Predicting the depth to economic temperatures pre-drill is one of the major barriers inhibiting the successful development of geothermal projects in Canada.

There are many ways to attempt to resolve the temperature of the Earth's crust. Surface heat flux measurements (e.g. Fuchs et al., 2024)do not accurately represent temperature at depth (Ball and Afonso, 2023; Sellers et al., 2023). Bottom-hole datasets used to extrapolate geothermal gradients within sedimentary sequences may locally yield high values (Weides & Majorowicz, 2014; Huang et al., 2020). But high sedimentary gradients should not be extrapolated into the Precambrian basement, because thse rocks may not have the same radioactive heat generation capabilities and their thermal conductivity values can be highly variable (e.g. Hyndman & Lewis,1999; Jessop, 1992). Curie Depth modelling has been historically used to predict the thermal structure of the crust, however, Ball and Afonso (2023) and Sellers et al., (2023) observed large errors in the depth estimates to Curie temperature (580oC) depths across Canada and the USA. Relying only on Curie Depth modelling can lead to significant errors in the geothermal gradient estimate. To solve this problem we have developed a method that focuses on the uncertainty relating to heat flow in the subsurface of Canada.

Method

The authors have developed a quantitative approach to connect and evaluate all available data and models. The approach was implemented in Geothermal Radar software for USA and Canada. For any given location, the thermal gradient is calculated based on 17 models (incl. aforementioned in "Theory") and corrected bottom-hole temperature measurements from existing wells (Figure 1a). As the models' and wells' locations differ relative to user-chosen point of interest, we perform spatial interpolation using inverse distance weighted (IDW) interpolation and local Kriging models.

The depth-to-temperature, temperature-at-depth and uncertainty levels, as well as original single-model data layers, are connected to real-time calculations and can be explored on a map (Figure 1b).



Figures 1a, 1b: *Existing wells with corrected bottom hole temperature and aggregated depth to 250C interactive data layers in Geothermal Radar (USA and Canada).*

The depth-temperature data points are overlayed by local-polynomial regression module simulating non-linear behavior of thermal gradient in any given location (Figure 2). Additionally, uncertainty levels are derived using models' spread and wells' data density. This allows to quantify individual quantiles of temperature predictions and p90/p10 ratio as a proxy for uncertainty levels.

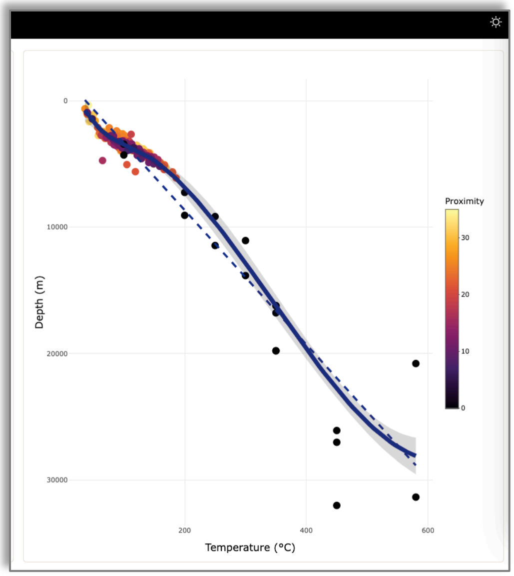


Figure 2: *Geothermal gradients calculated in Geothermal Radar within an uncertainty range. Temperature range from 10℃ to 580℃.*

Additionally, by taking datasets from LithoRef18 for crustal density (Afonso et al., 2019) and integrating sediment thickness (e.g. Laske et al. 1997) with density-depth calculations (e.g. Sykes 1996) we calculate on the fly the lithostatic and hydrostatic pressure gradients to any location desired (Figure 3).

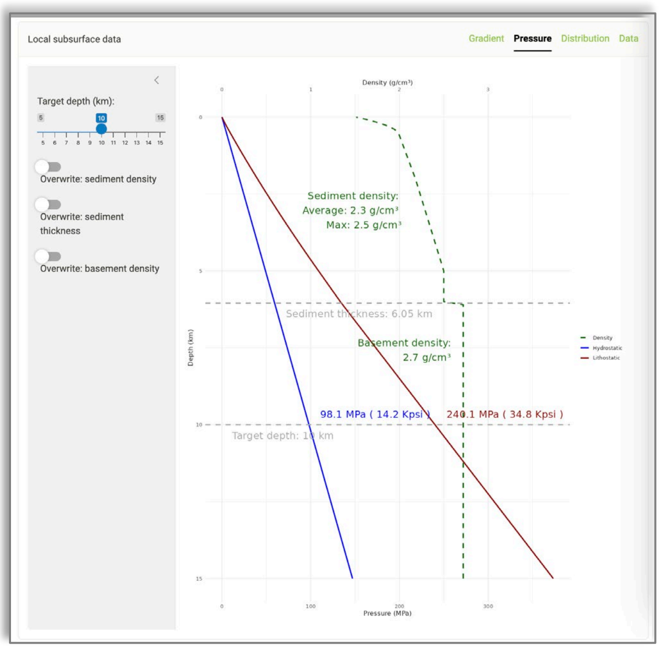


Figure 3*: Pressure prediction for geothermal targets, with a hypothetical drill target of 10 km.*

Novel/Additive Information

This meta-study and its interactive implementation allow displaying all existing data and models together and perform cross-model evaluation, including aggregated gradient and uncertainty levels quantification.

The thermal component is combined with hydrostatic and lithostatic pressure gradient down to the depth of hypothetical geothermal targets allowing for screening with thermodynamic constrains.

We believe that by computing geothermal gradients in the sedimentary rock sequence and crystalline basement we can aid the exploration and rapid screening of geothermal opportunities in Canada in two ways. Firstly, we can help select sites with the lowest uncertainty range with respect to the desired economic temperatures. Secondly, by understanding uncertainty in depth to economic temperature, we can facilitate discussions and priority data to reduce the uncertainty and the pre-drill risks in a geothermal project.

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