Evaluation of the Precambrian Basement Temperature Below Four South Slave Communities, Northwest Territories, Canada

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ABSTRACT

Fort Providence, Kakisa, Hay River, and Enterprise are four South Slave communities located in the Northwest Territories (Canada). These communities rely on fossil fuels for space and water heating, and could benefit from geothermal systems. The South Slave Region is estimated to have the highest heat flow (>100 mW m^{-2}) in the Western Canadian Sedimentary Basin (WCSB), therefore is a target for geothermal exploration. However, an analysis of the deep geothermal resources has not been undertaken in this region. This research project objective is to fill this knowledge gap by providing a Precambrian basement temperature assessment below the sedimentary basin, around the four communities.

The Devonian sedimentary rock sequence on which the communities lie is thin (500 to 750 m) and has relatively low permeability (on average $<10^{-14}$ m^2). The lack of information on the Precambrian basement below Devonian sedimentary rocks limits the development of deep geothermal energy resources due to high uncertainty and risk. Deep borehole heat exchangers (DBHE) could be an appealing technology for direct use of heat in this geological context. However, a comprehensive assessment requires a detailed understanding of the thermal properties of the rocks. This information is mandatory to model such systems and provide accurate temperature estimates at depth.

A rock sampling campaign focusing on the Precambrian basement rocks was made in summer 2023, during which 91 outcrops and drilling cores were sampled to analyze their thermal properties. A range of thermal conductivity expected in the Precambrian basement was determined for the location of each community. Then, the results were used to extrapolate the subsurface temperature in the Precambrian basement until 10 km depth. The newly available information confirmed the presence of a significant geothermal potential in these communities.

In the more likely scenario (the normal one), the temperature at the top of the Precambrian basement ranges from 30.5 to 36.5 °C, with a basement surface heat flow of 99 mW m^{-2} to 157.7 mW m^{-2}. At 3 km depth, the temperature ranges from 100.4 to 156 °C; at 10 km depth, the temperature ranges from 303.6 to 511.6 °C for each community. Hay River has the highest values and most promising geothermal potential for deep closed-loop systems.

1. Introduction

Energy costs in northern Canada, populated by several indigenous communities, are higher than in the rest of the country. For example, electricity rates in the Northwest Territories (NWT) are more than twice the national average (Canada Energy Regulator & Government of Canada, 2023). The NWT, like many other northern regions, mainly relies on carbon-intensive fossil fuels such as oil to meet its electricity, space heating, and water heating needs. The Government of the NWT aims to ensure a balance between energy security, affordability, and reduction of greenhouse gas emissions in its 2030 Energy Strategy (Government of Northwest Territories, 2018). Key initiatives include replacing diesel with renewable energy solutions by exploring the potential of technologies such as deep geothermal resources in areas that have been identified as having high geothermal potential (EBA Engineering Consultants Ltd., 2010). These areas have yet to be defined and characterized.

This research project focuses on the geothermal potential of four communities in the southern part of the NWT with the intent of characterizing its deep geothermal resources. The communities (Figure 1) are located within the South Slave administrative region, part of the Dehcho First Nations: Hay River (Xátł'odehchee, K'atlodeeche First Nation and Ts'ueh Nda, West Point First Nation), Fort Providence (Zhahti Kų́ę́, Deh Gáh Got'îê First Nation), Enterprise, and Kakisa (K'ágee, Ka'a'gee Tu First Nation). Due to their close vicinity, Hay River Town and Hay River Dene (Katlodeeche First Nation Reserve) are referred to as "Hay River" in the study.

These four communities are situated within the largest high heat flow anomaly in Canada, known as the Northern Plains Heat Flow Anomaly (NPHFA) or Northern Anomaly (Majorowicz, 1996; Majorowicz & Weides, 2014). This anomaly is approximately 300 km wide and stretches 500 km from north to south. The geothermal gradient and heat flow in the research areas are significantly higher compared to other Precambrian platform locations worldwide (Majorowicz & Jessop, 1981). Several hypotheses have been proposed to explain the thermal anomalies in this region. Bachu (1993) suggested that the unusually high temperatures measured could be related to hydrogeological effects which can disturb heat flow patterns. Majorowicz (1996) suggested the presence of an increased mantle upflow beneath the region which aligns with other heat flow anomalies along the western margin of the North American Craton. Despite these hypotheses, Majorowicz (2018) concluded that the exact cause of the heat flow anomaly remains speculative.

Rajaobelison et al. (In press) measured thermophysical properties on the NWT South Slave's sedimentary rocks. Then, Rajaobelison et al. (2024) created 1D temperature models based on temperature data from vintage oil and gas wells to evaluate the geothermal potential in the sedimentary sequence of NWT South Slave's communities.

Due to the generally low permeability and porosity inferred for the matrix of the sedimentary rocks analyzed in these studies and the shallow depth of the basement (525 to 729 m), the potential technologies that can be envisioned to produce geothermal energy are closed-loop DBHE relying on conduction to extract heat from rock formations and/or enhanced geothermal systems (EGS) requiring stimulation of potential reservoir formation to extract heat by forced convection.

A temperature model for the Precambrian basement, which lies below the sedimentary sequence, could not be made in previous studies due to a lack of information on the basement thermal properties. Very little information and data exist about the basement below the communities, representing a limitation when it comes to understanding and assessing the geothermal resources of the region. To reach higher temperatures below the sedimentary cover (>37 °C, Rajaobelison et al., 2024), Precambrian basement depth must be considered.

Therefore, this study objective is to assess the temperature at depths within the basement rock beneath the communities. To achieve this goal, we intend to determine a range of thermal properties for each tectonic domain (i.e., the Precambrian bedrock underlying each community). Additionally, we wish to extend previous work on sedimentary sequences (Rajaobelison et al., 2024) by incorporating new data from previously unsampled formations. This will help reduce uncertainties related to the rock thermal properties and temperature calculation at depth.

2. Geological Settings

The four NWT communities are located on the eastern edge of the WCSB. It is positioned between the Cordilleran Orogen to the west and the Canadian Shield to the east (Figure 2). Significant oil and gas exploration activities have taken place since the 1950s, with over 400 exploration wells drilled, most of which are now abandoned (OROGO, 2024) but has contributed to the identification of the high geothermal potential in the area (Figure 1).

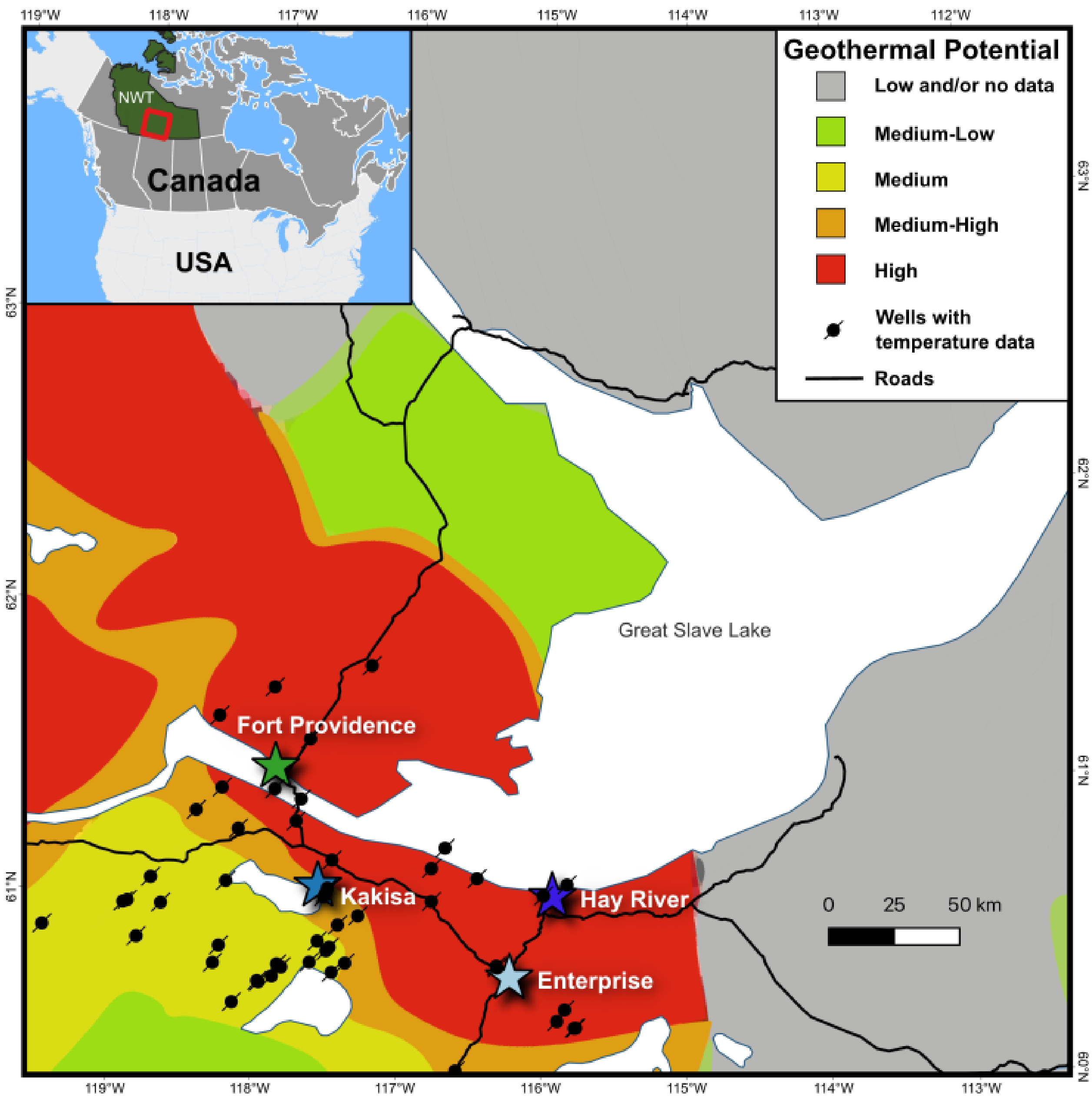

Figure 1: Geothermal potential map based on temperature (adapted from EBA Engineering Consultants Ltd., 2010) showing wells (abandoned) with temperature data and community locations.

The Quaternary glacial sediment, often called soil or alluvium, is between 4 m and 20 m thick at the community's location. It was deposited unconformably over the Paleozoic-Cenozoic sedimentary rock formations.

The sedimentary rocks lie on the top of a Precambrian crystalline basement that is part of the Canadian Shield. The sedimentary strata gradually thicken from east-northeast to west-southwest, ranging from about 500 m to 715 m in thickness at the community's locations. Furthermore, the geological formations in the region exhibit low porosity and permeability, implying a limited potential for hot sedimentary aquifers, as noted by Rajaobelison et al. (In press). The anticipated permeability is expected to be mostly influenced by fault and fracture networks rather than the intrinsic porosity of the formations. Conduction is the dominant mechanism for geothermal heat flow in the region (Bachu, 1993; Gray et al., 2012; Majorowicz et al., 1999; 2012), which is the focus of the present study.

The Precambrian basement underlying the sedimentary cover consists of a poorly known mix of igneous and metamorphic rocks. It is characterized and subdivided by tectonic domains (Figure 2). The domains in the study area, listed from east to west and in chronological order of age are; Slave Craton, Great Bear Magmatic Zone, and Hottah Terrane that is part of Wopmay Orogen accreted terranes (Ootes et al., 2015). All tectonic domains of the Precambrian basement have various compositions, ages and tectonic histories, as well as different thermal properties that are critical for geothermal assessment. Thus, we employ tectonic domain terminology in this study to address basement classification. Hay River and Enterprise are part of the Slave Craton tectonic domain. Fort Providence and Kakisa, on the other hand, are located in Hottah Terrane.

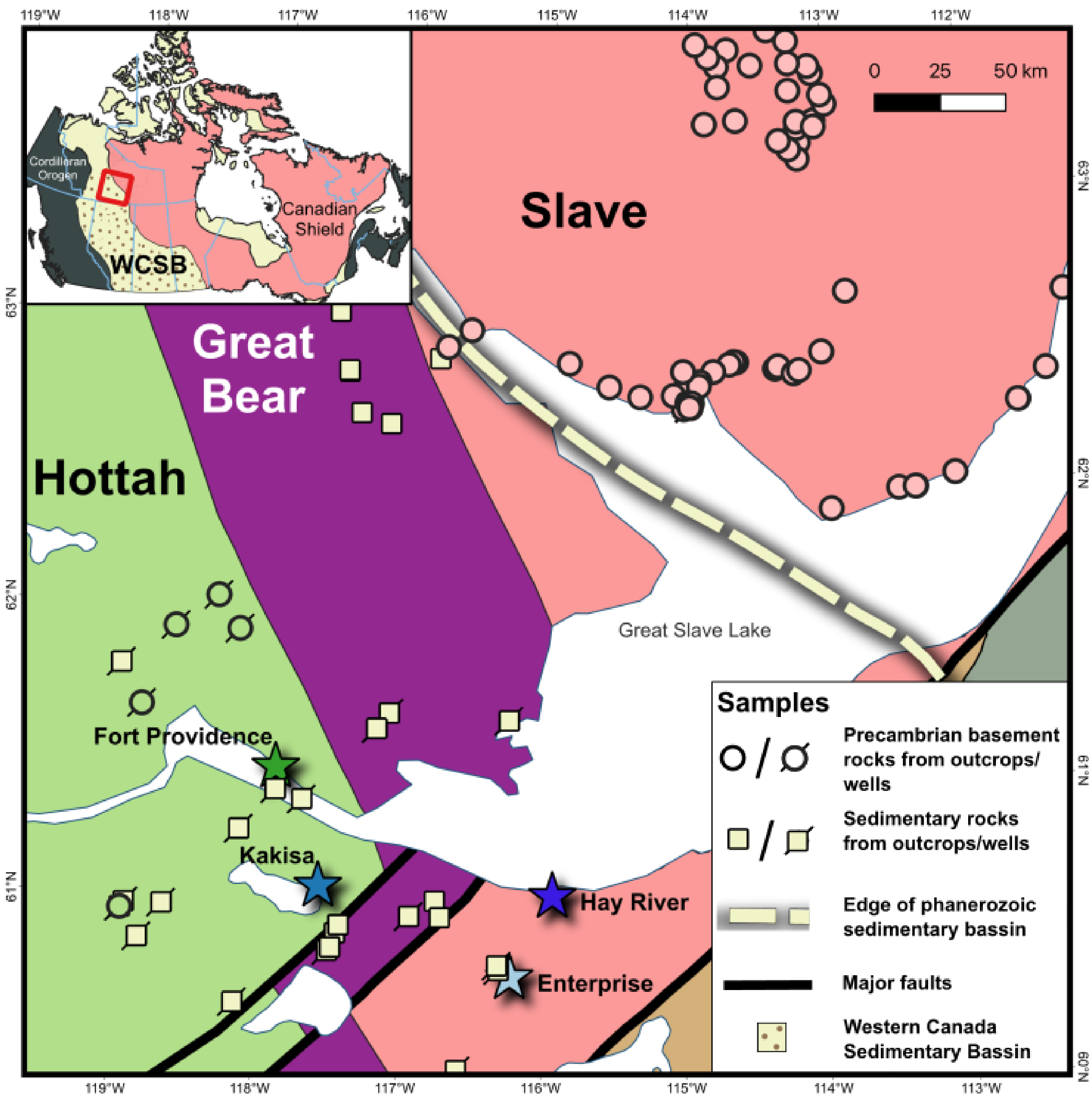

Figure 2: Tectonic domain map (based on Ootes et al. (2015) domain division), with samples and community locations.

3. Material, Methods and Input Data

To accurately predict temperature at different depths, it was essential to use representative input data that accurately reflected the geological characteristics of the location. Due to the lack of information on thermal properties for geological materials in this area, we conducted extensive sampling and laboratory measurements. Collected data was used as input and is the foundation of subsequent analyses and thermal assessment. We therefore present below an updated thermostratigraphic assessment, providing a new comprehensive dataset for the Precambrian bedrock and enhancing the previous sedimentary rocks sequence data.

This section gives an overview of the sampling process, thermal property analysis, undisturbed ground temperature assessment, input data and scenario examination, and a comprehensive thermostratigraphic assessment. All this information was used to create temperature profiles until the basement's top, 3 km and 10 km depths, which are the main results of this research.

3.1 Sampling overview

In 2022, we sampled 84 split core samples from 43 vintage oil and gas exploration wells of the South Slave region. Related descriptions and laboratory results are presented in Rajaobelison et al. (In press). Some sedimentary formations under the communities remained unsampled and thermal conductivity values from literature were assigned based on their lithologic content.

A rock sampling campaign in 2023 allowed the collection of 91 Precambrian basement rock samples, for which we think to have recovered a variety of geological units of each tectonic domain related to each community that could give us a good approximation of the material that can be encountered under these communities (Table 1). Sedimentary rocks sampling was partial and had to be interrupted due to forest fires and an evacuation order in the area (Figure 3).

Table 1: Sampling overview.

Geological material			Number of samples		
Alluvium					3
Sedimentary Rocks					112
Precambrian Basement Rocks	Igneous	Plutonic	54	66	91
		Volcanic	12		
	Metamorphic	Sedimentary	16	25	
		Plutonic	5		
		Volcanic	4		

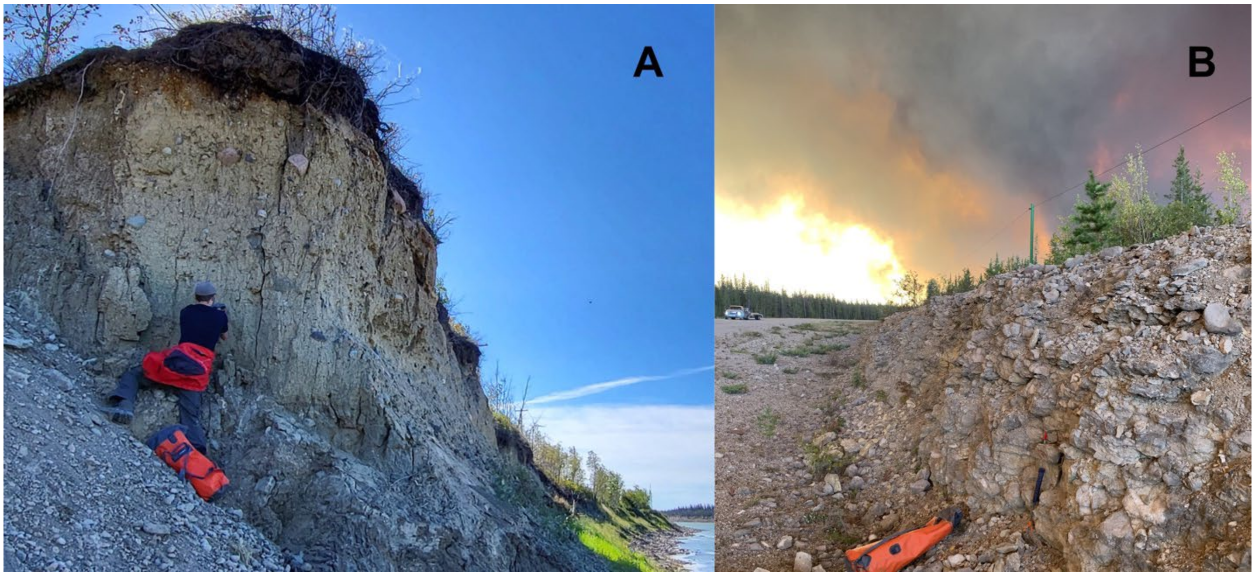

Figure 3: A) Soil sampling in Fort Providence on a glacial till cliff along the DehCho Dr road. B) Sedimentary rock outcrop sampling on the roadside of Highway 1 between Kakisa and Enterprise, one of the last samples before the evacuation order.

3.2 Thermal Properties

3.2.1 Thermal Conductivity

All sedimentary and basement rock samples collected (Table 1) were analyzed for thermal conductivity. The methodology follows that of Rajaobelison et al. (In press). Transient measurements were made using an optical scanning instrument developed by Popov et al. (2023) under dry conditions (Figure 4).

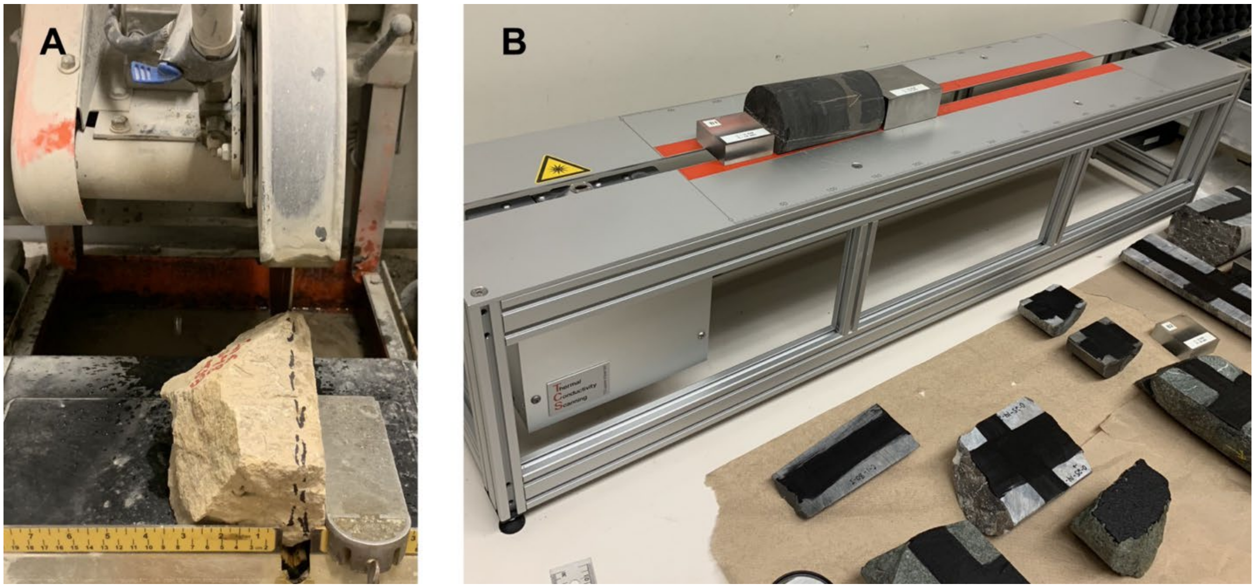

Figure 4: Sample preparation and analyses. A) Rock sample saw cutting. B) Thermal property measurement on the optical scanning instrument developed by Popov et al. (2023).

The average thermal conductivity values for all the measured samples, presented by types of material are shown in Figure 5. The classification of rocks according to their insulating to conductive potential indicated on Figure 5 and 6 is based on Rajaobelison et al. (In press), Sass & Götz (2012) and Sass et al. (1992).

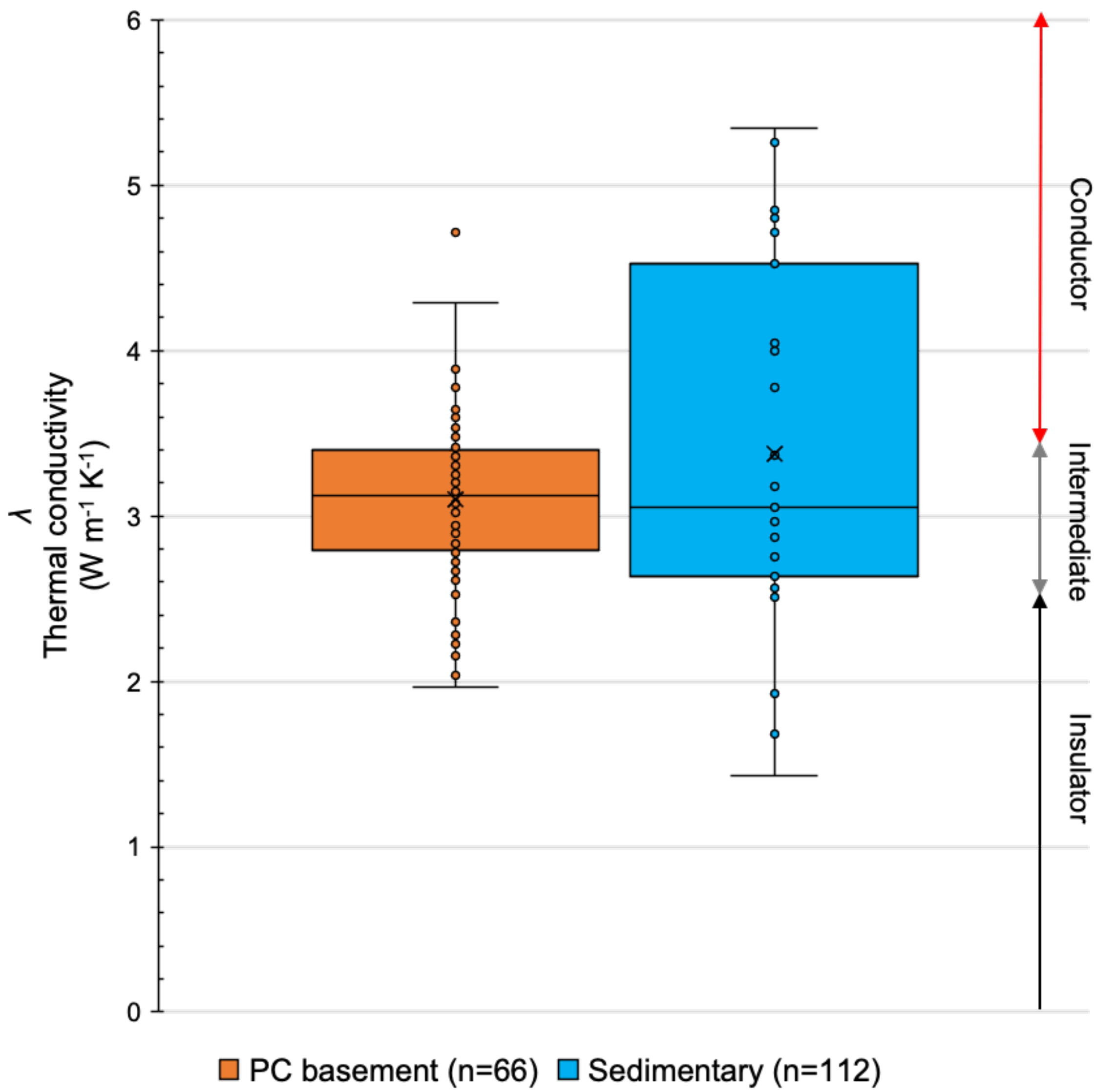

Figure 5: Thermal conductivity for the overall sampled Precambrian (PC) basement and sedimentary rocks.

In this study, we treat each tectonic domain (Figure 2) as a uniform thermal unit. Sixty-six samples from the outcropping Slave Province were analyzed for the Slave Craton tectonic domain, which is associated with the Hay River and the Enterprise Precambrian basement. For the Hottah Terrane tectonic domain (Fort Providence and Kakisa), we sampled eleven core cuttings and surface rocks. We added ten additional previously measured core cuttings from other locations in our data set, which came from Majorowicz et al. (2014). Figure 6 shows the corresponding thermal conductivity ranges.

The values attributed to the Slave Craton account for a wide range of lithologies that represent practically all geological units visible at the surface of the Slave Province, from which these Precambrian structures extend beneath the sedimentary layer (Ootes et al., 2015). The Hottah Terrane has slightly higher thermal conductivity values, a broader spread, and fewer samples.

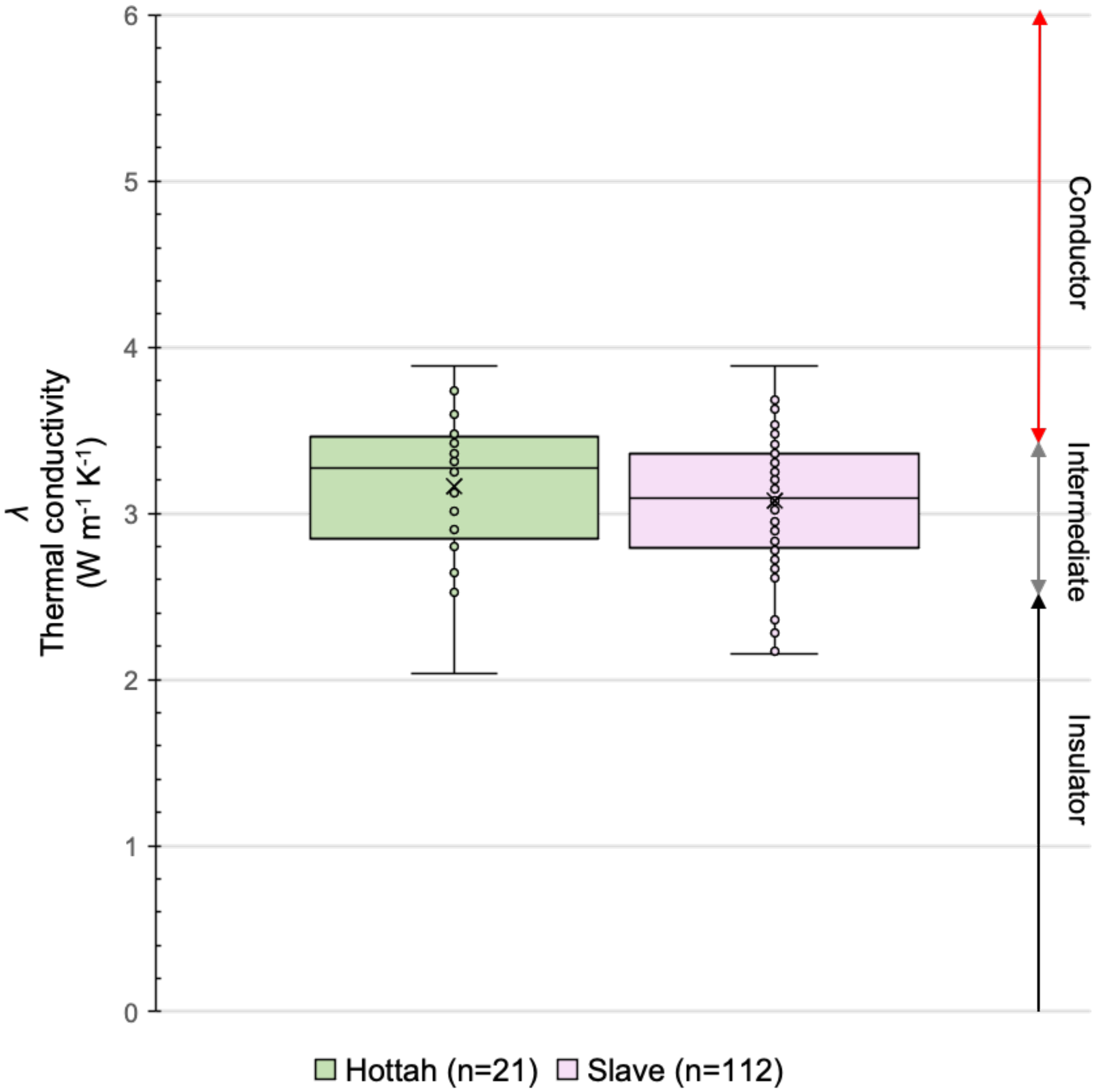

Figure 6: Thermal conductivity for basement domain related to each community.

3.2.2 Heat Generation Rate

Table 3 shows the heat generation rate expected for sedimentary units and basement domain. The sedimentary formations values were obtained from Rajaobelison et al. (2024). The basement heat generation rate was determined according to literature values specific to each tectonic domain, including Jessop (1992) for the Hottah Terrane and Perry et al. (2010) for the Slave Craton.

3.3 Undisturbed Ground Temperature

The undisturbed ground temperature T_s (K) was estimated using the equation proposed by Ouzzane et al. (2015):

$$T_s = 17.898 + 0.951 T_{amb} \quad (1)$$

where T_{amb} (K) is the ambient air temperature, which is considered to be -2.5 °C based on the mean annual air temperature from the Hay River-A weather station (Government of Canada & Environment and Natural Resources, 2024). T_s is thus estimated to be 2.1 °C in the South Slave region.

3.4 Input Data and Scenarios

In this study, various scenarios were proposed based on the probabilistic distribution of thermal properties. This provides for a normal, pessimistic, or optimistic outlook. These are presented in Table 2 as input for thermal properties and in Table 3 as results.

The normal scenario employs the 50th percentile (P_{50}) values of basement thermal conductivity, heat generation rate, as well as the heat flow and geothermal gradient acquired from the corrected well temperature measurements, resulting in a neutral approach. The pessimist scenario uses the 25th percentile (P_{25}) value of heat flow and temperature gradient, the minimum heat generation rate value and the 75th percentile (P_{75}) percentile values for the thermal conductivity, embodying a cautious approach. In contrast, the optimist scenario utilizes P_{75} values for heat flow and temperature gradient, the maximum heat generation rate, and P_{25} values for the thermal conductivity, providing insight into best-case scenarios. These diverse perspectives allowed for a comprehensive analysis of potential outcomes across different scenarios.

Table 2. Thermal properties (thermal conductivity and heat generation rate) values assigned to each scenario (normal (N), pessimist (P) and optimist (O)) for each community in the sedimentary sequence and the Precambrian (PC) basement (Hottah Terrane and Slave Craton tectonics domain). The number of samples is denoted by *n*.

			λ Thermal Conductivity (W m^{-1} K^{-1})				**A** Heat Generation Rate (μW m^{3})			
			n	N P_{50}	P P_{75}	O P_{25}	*n*	N P_{50}	P min	O max
Sedimentary		Fort Providence	80	2,5	2,8	2,4	80	0,5		
		Kakisa		2,3	2,7	2,2		0,4		
		Hay River		2,8	3,1	2,5		0,4		
		Enterprise		2,6	2,8	2,4		0,4		
PC basement	Hottah	Fort Providence, Kakisa	21	3,3	3,4	2,9	7	2,1	1	3,6
	Slave	Hay River, Enterprise	66	3,1	3,4	2,8	20	2,3	1	4,8

3.5 Thermostratigraphic Assessment

Temperature was calculated at the base of each sedimentary rock units and at each 500 m intervals in the basement. To be consistent with previous work, we used for each community the same well temperature data listed in the assessment of Rajaobelison et al. (2024), where well temperature measurements from drill-stem tests (DST) and borehole temperature (BHT) were corrected for drilling disturbance and paleoclimate effects. This temperature assessment of the sedimentary basin served as inputs for the present temperature assessment in the Precambrian basement.

3.5.1 Paleoclimate corrections

Past glaciations in Canada lowered subsurface temperatures at shallow depths, due to both the cooling effects of lower surface temperatures and crustal compression induced by the weight of ice sheets that covered the land. These paleoclimate effects persist today to consideradable depth, necessitating paleoclimate corrections in temperature assessments for accurate deep geothermal estimations out of shallow wells temperature measurements (Jessop, 1992). The effects of past glaciations in Canada can be significant to the depth of two kilometres or more (Bédard et al., 2016; J. Majorowicz, Chan, et al., 2014; J. Majorowicz et al., 2012). While this influence diminishes with depth, it's essential to account for paleoclimate corrections, particularly for this area where temperature measurements from old oil and gas exploration wells are mainly less than a thousand metres deep. Beyond a certain depth, temperatures tend to reach equilibrium, reflecting the long-term geothermal gradient of the region. In this study we consider a depth of 3 km, from which climatic variations no longer have a significant impact on temperature and that we consider as equilibrium temperature. The 3 km cut-off value for the South Slave region seems reasonable, considering that northern Alberta estimates are 2200 m based on the first heat flow measurement in a well that reached the basement under the WCSB below the depth of the paleoclimatic influence (Majorowicz, Chan, et al., 2014; Majorowicz et al., 2012). In areas where paleoclimates have a deeper influence, such as the St. Lawrence Lowlands sedimentary basin in Quebec (Bédard et al., 2016; Chapelet, 2022), the influence on temperatures and heat flow are minimal below 3 km depth. The equilibrium temperature at depth $T_{z\,(\mathrm{eq})}$ is calculated with the following paleoclimate correction equation (Jessop, 1990; Rajaobelison et al., 2024):

$$T_{z(\mathrm{eq})} = T_\mathrm{m} + \sum_\mathrm{i}(T_\mathrm{i}) \left[erf\left(\frac{z}{2\sqrt{\alpha\, t_1}}\right) - erf\left(\frac{z}{2\sqrt{\alpha\, t_2}}\right)\right] \tag{2}$$

where T_m (°C) represents the temperature measured at a certain depth z (m), corrected from drilling disturbance and T_i (°C) is the temperature step between glaciations. The error function is represented by *erf*, α ($m^2\,s^{-1}$) is the mean thermal diffusivity of the rocks, t_1 (s) represents the end of the ice age, while t_2 (s) represents the beginning of the ice age. Specific information regarding the values employed can be found in the laboratory and thermostratigraphic studies conducted by Rajaobelison et al. (2024).

Thus, to estimate the actual subsurface temperature at a depth of less than 3 km, the paleoclimatic correction (equation 2) was removed such that temperature is characteristic of the value that can be measured (i.e., affected by glaciation). However, the paleoclimate correction was applied to calculate temperature until 10 km depth since glaciations are expected to have a low impact at great depth.

3.5.2 Geothermal Gradient

The geothermal gradient g (°C m^{-1}) refers to the rate at which temperature increases with depth below the Earth's surface. It can be stated by the following:

$$g = \frac{\Delta T}{\Delta z} = \frac{T_z - T_s}{z} \tag{3}$$

where ΔT (°C) is the difference between the temperature at the depth being assessed T_z (corrected measured temperature are from Rajaobelison et al., 2024) and the undisturbed ground temperature (T_s = 2.14 °C), and z (m) is the depth of the corrected temperature assessed.

3.5.3 Surface Heat Flow

Heat flow in the context of geothermal energy refers to the movement of thermal energy from the Earth's interior toward the surface, often used to assess the potential for geothermal energy extraction. Surface heat flow Q_0 (W m^{-2}) quantifies the rate at which this heat energy is transferred per unit area over the Earth's surface. The following equation (Bédard et al., 2016; Jessop, 1990; Rajaobelison et al., 2024) is used to compute surface heat flow in a sedimentary basin:

$$Q_0 = \lambda_{\text{sed}} g + A_{\text{sed}} \frac{z}{2} \tag{4}$$

λ_{sed} (W m^{-1} K^{-1}) denotes the effective thermal conductivity of the sedimentary sequence, determined by calculating the weighted harmonic mean of the λ for the different lithologic units that make up the sedimentary rock cover at each location, g (°C km^{-1}) refers to the geothermal gradient determined from temperature measurements as described previously, A_{sed} (W m^{-3}) is the effective heat generation obtained from the weighted arithmetic average in the sedimentary rock sequence and z (m) is the rock sequence thickness between the measured temperature depth and the ground surface.

3.5.4 Basement Heat Flow

The basement top heat flow Q_{PC} (W m^{-2}) is defined here as the heat flow at the boundary between the sedimentary layers and the underlying Precambrian basement rocks. It is calculated by removing the heat generation effects A_{sed} within the sedimentary rocks from the surface heat flow through the sedimentary sequence, according to the following equation (Bachu, 1993; Bédard et al., 2016; Majorowicz, Nieuwenhuis, et al., 2014; Majorowicz & Grasby, 2010b):

$$Q_{PC} = Q_0 - A_{\text{sed}} \frac{z_{\text{sed}}}{2} \tag{5}$$

where z_{sed} is the thickness of the sedimentary rocks sequence, which is the depth between the top of the Precambrian basement and the ground surface.

3.5.5 Temperature at Depth in the Sedimentary Rocks Sequence

Each sedimentary rock formation has a distinct effective thermal conductivity λ, hence the temperature at depth $T_{z(\text{sed})}$ (°C) was calculated at their boundaries. It was computed analytically under steady-state condition, taking into account conductive heat transfer using a one-dimensional approach (Rajaobelison et al., 2024; Stein, 1995):

$$T_{z(\text{sed})} = T_s + \frac{Q_0 z}{\lambda} - A \frac{z^2}{2\lambda} \tag{6}$$

where Ts (°C) is the temperature at the base of the sedimentary formation, z (m) the formation thickness and λ (W m^{-1} K^{-1}) the formation effective thermal conductivity.

3.5.6 Temperature at Depth in the Precambrian Basement

The temperature at any depth in the Precambrian basement $T_{z(\mathrm{PC})}$ was calculated at each 500 m intervals, using the same relationship mentioned above for $T_{z(\mathrm{sed})}$:

$$T_{z(\mathrm{PC})} = T_{PC} + \frac{Q_{\mathrm{PC}}\, z_{\mathrm{PC}}}{\lambda_{\mathrm{PC}}} - A_{PC}\frac{z_{PC}^{2}}{2\lambda_{\mathrm{PC}}} \quad (7)$$

where T_{PC} (°C) is the temperature at the top of the basement, Q_{PC} (W m^{-2}) is the basement heat flow, z_{PC} (m) is the depth from the top of the basement, λ_{PC} (W m^{-1} K^{-1}) the thermal conductivity of the basement and A_{PC} (W m^{-3}) is the heat generation of the basement rocks.

4. Results

4.1 Input data

Table 3 presents the calculated geothermal gradient and surface heat flow for the sedimentary sequence, which were used in the temperature calculations.

Table 3: Geothermal gradient and heat flow assigned to each scenario (normal (N), pessimist (P) and optimist (O)) for each community (Fort Providence (FP), Kakisa (K), Hay River (HR) and Enterprise (E)) in the sedimentary sequence.

		g Geothermal Gradient (°C km^{-1})			g_{eq} Equilibrium (°C km^{-1})			Q_0 Surface Heat Flow (W m^{-2})			$Q_{0(eq)}$ Equilibirum (W m^{-2})		
		N	P	O	N	P	O	N	P	O	N	P	O
		P_{50}	P_{25}	P_{75}	P_{50}	P_{25}	P_{75}	P_{50}	P_{25}	P_{75}	P_{50}	P_{25}	P_{75}
Sedimentary	FP	53	43	56	56	47	58	133	104	158	141	112	166
	K	43	39	44	45	41	46	99	85	118	105	90	125
	HR	56	46	61	59	50	64	158	115	186	167	124	195
	E	41	37	43	44	39	46	106	88	120	113	93	129

4.2 Temperature in the Sedimentary Rocks Sequence

Each temperature point used for calculations in the sedimentary rock sequence corresponds to the top of each sedimentary formation (fm.; Figure 7). The calculated temperature is based on heat flow assessed in wells near the communities. The profiles represent an estimate of the current temperature found in the sedimentary rocks, thus affected by glaciations and uncorrected for paleoclimates.

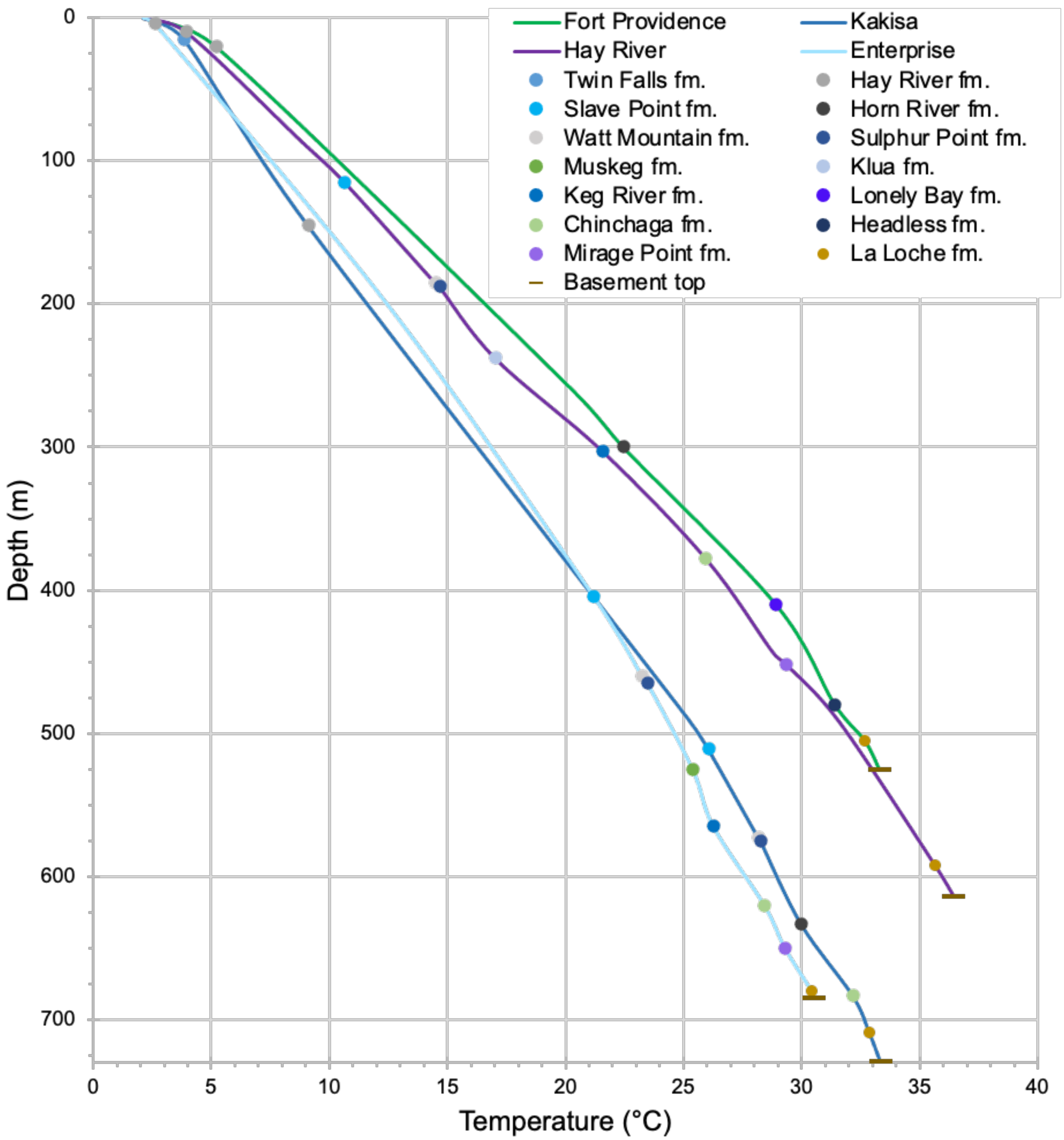

Figure 7: Temperature at depth in the sedimentary sequence, with normal scenarios, considering heat flow uncorrected for paleoclimates. Each community is represented by a distinct coloured line, and each geological formation (fm.) top is represented by a specific coloured circle.

4.3 Temperature in the Basement until 3 km depth

The temperature calculated until 3 km depth (Figure 8, 9, 10, 11, 12) incorporates uncertainty scenarios. The calculated temperatures represent an estimate of expected and current temperatures found in the basement, thus affected by glaciations and uncorrected for paleoclimates.

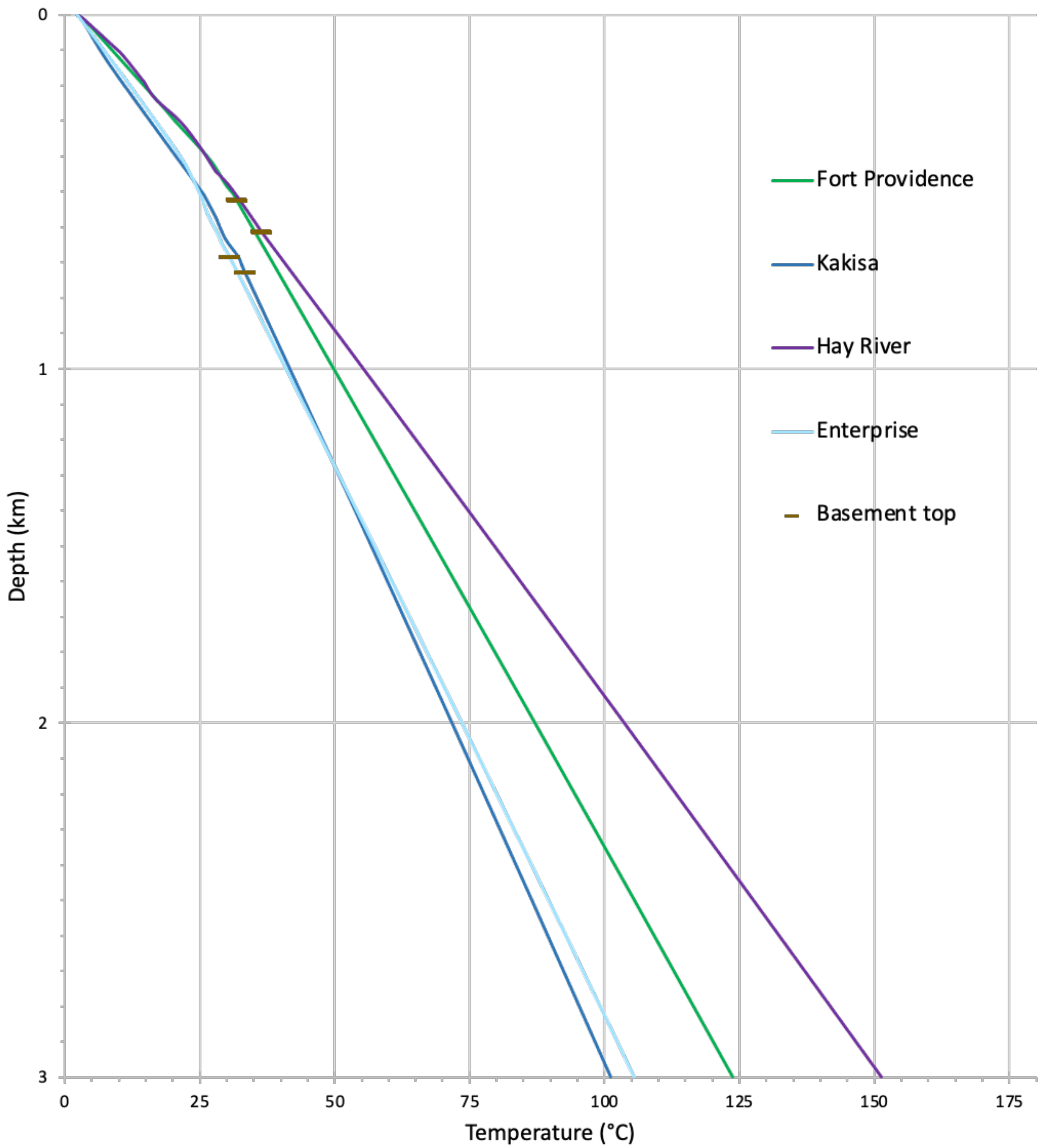

Figure 8: Temperature until 3 km depth, with normal scenarios, considering heat flow uncorrected for paleoclimates. Each community is represented by a distinct coloured line.

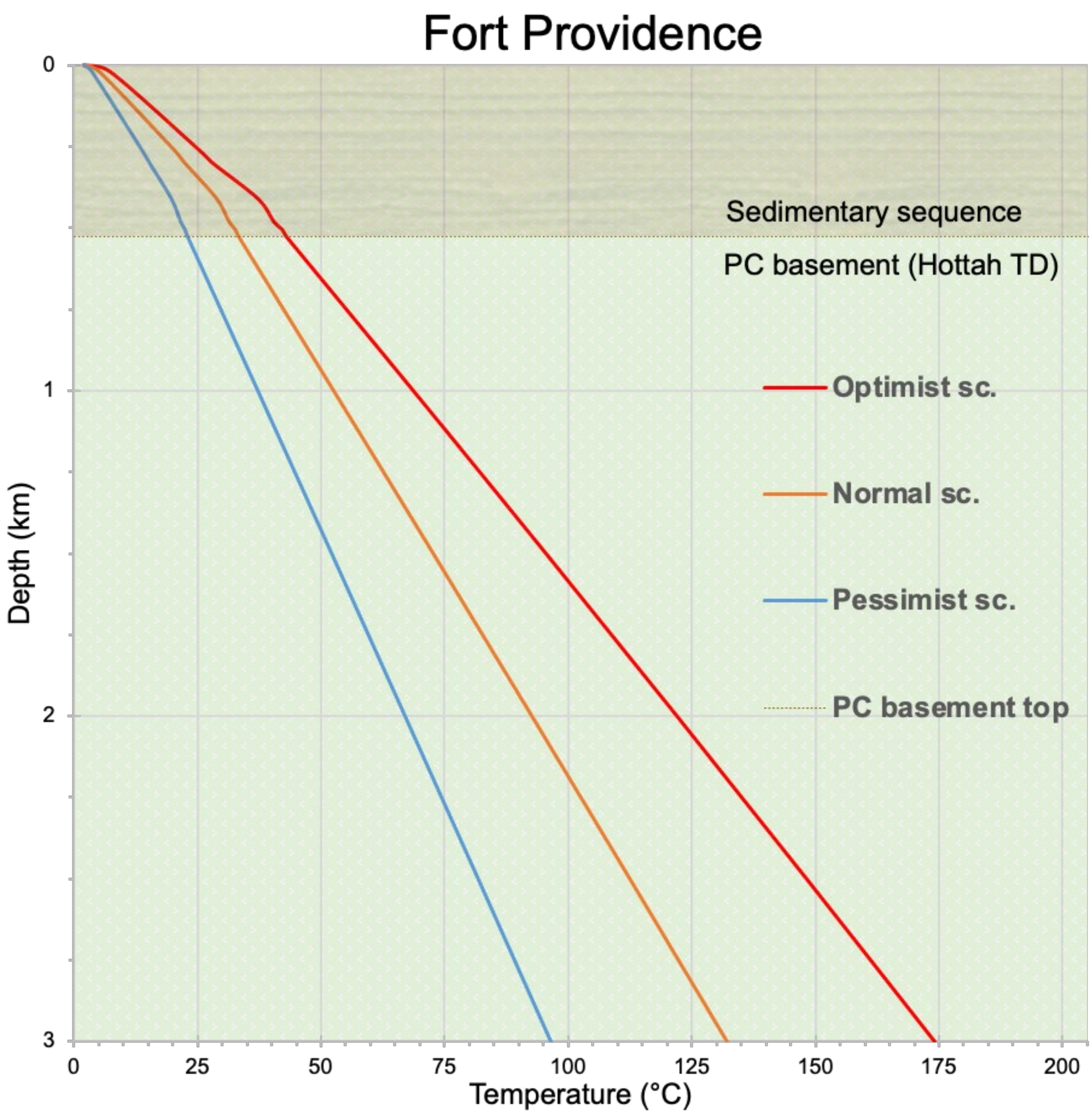

Figure 9: Temperature until 3 km depth for Fort Providence, with optimist, normal and pessimist scenarios, considering heat flow uncorrected for paleoclimates.

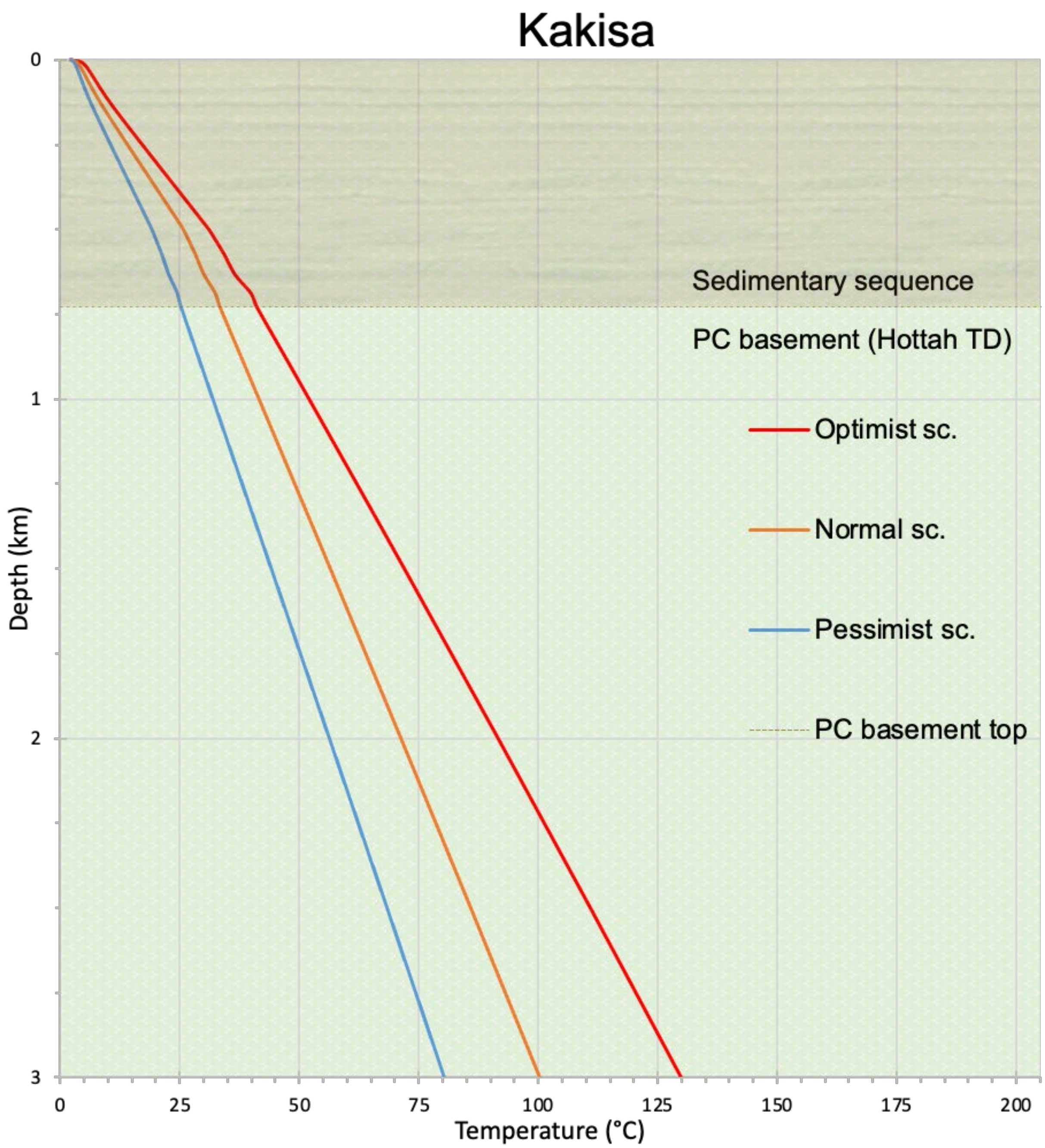

Figure 10: Temperatures at depth until 3 km depth for Kakisa, with optimist, normal and pessimist scenarios, considering heat flow uncorredted for paleoclitates.

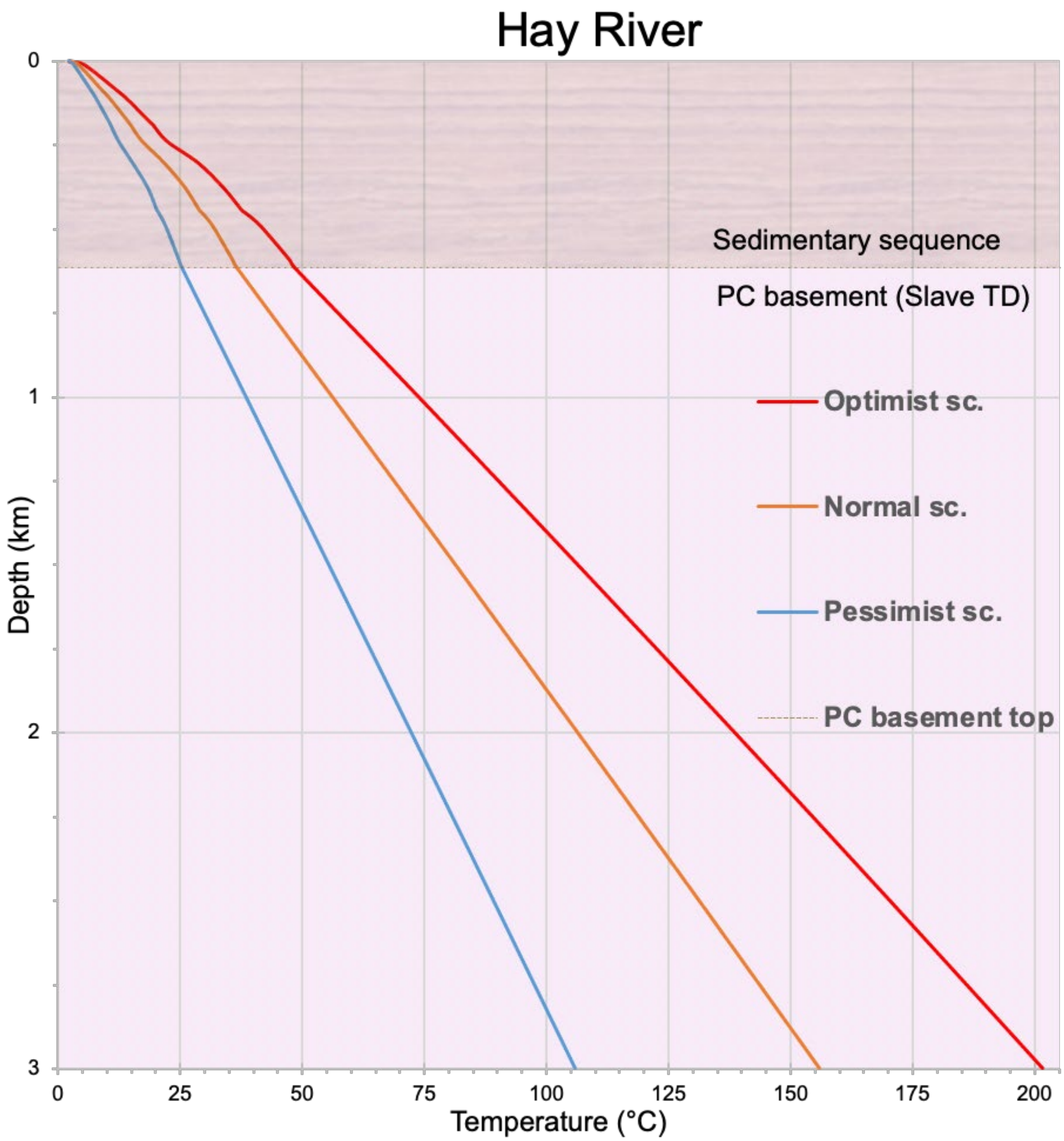

Figure 11: Temperatures at depth until 3 km depth for Hay River, with optimist, normal and pessimist scenarios, considering heat flow uncorrected for paleoclimates.

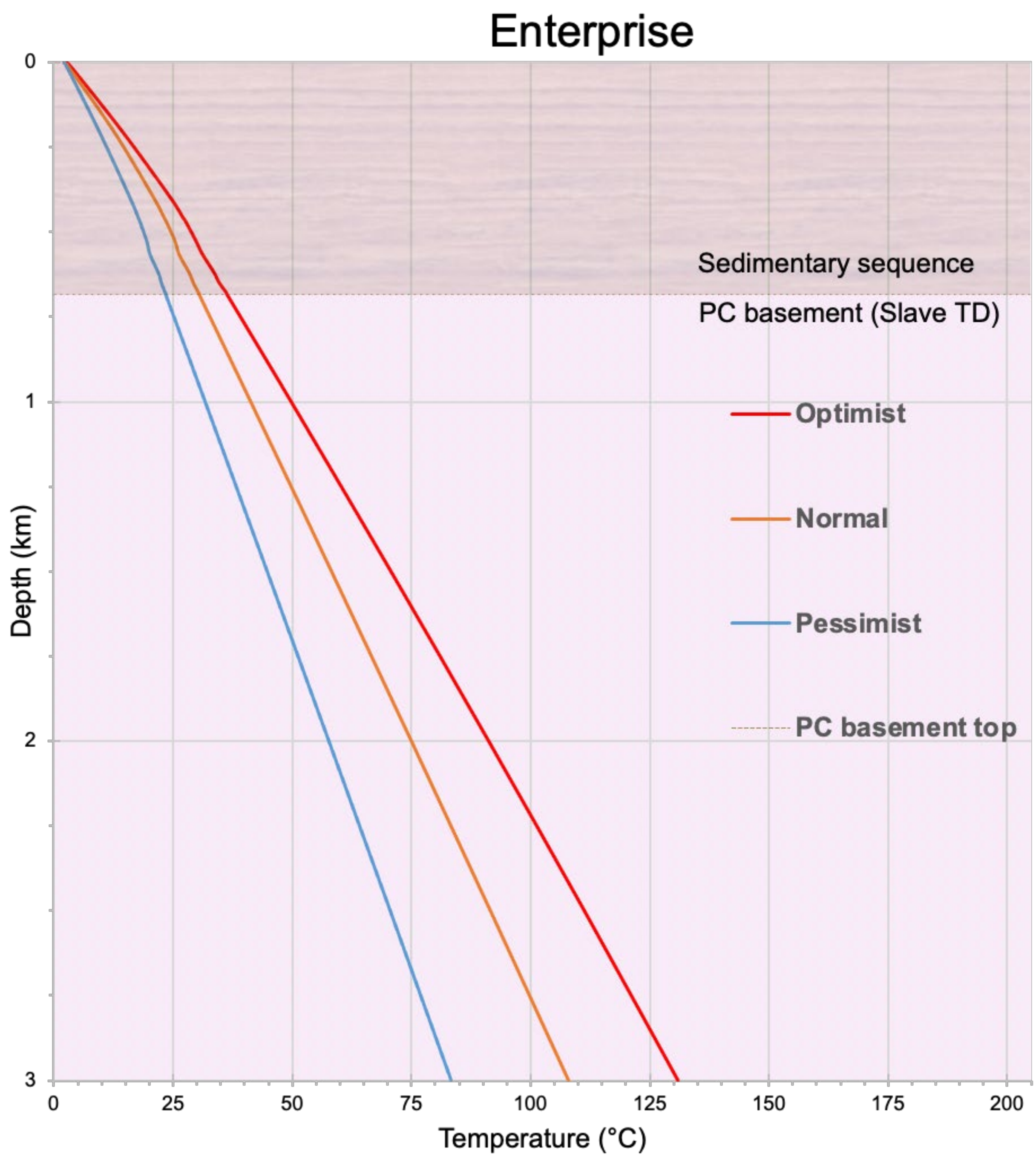

Figure 12: Temperatures at depth until 3 km depth for Enterprise, with optimist, normal and pessimist scenarios, considering heat flow uncorrected for paleoclimates.

4.4 Temperature in the Basement until 10 km depth

For the sake of clarity, only the normal scenario is considered for the temperature calculated until 10 km depth below each community (Figure 13). The calculated temperatures represent an estimate of the equilibrium temperature, considering heat flow corrected for paleoclimates.

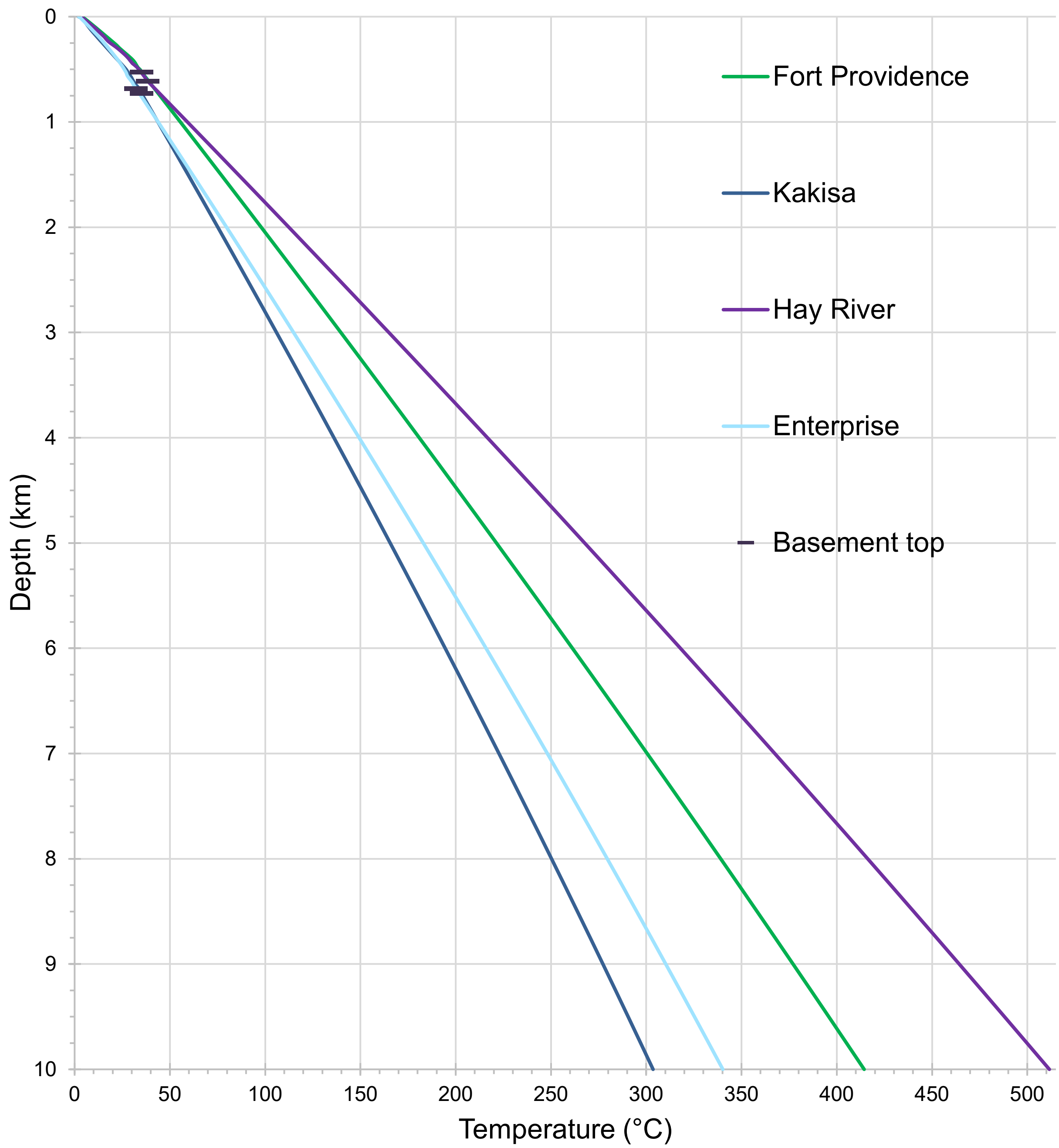

Figure 13: Temperature until 10 km depth, with the normal scenario, considering equilibrium heat flow, corrected from paleoclimate effects. Each community is represented by a distinct coloured line.

5. Discussion

This basement thermal property assessment allowed to predict temperature at depth below the sedimentary rock cover for the NWT communities of Hay River, Fort Providence, Enterprise, and Kakisa. The new thermal properties data present in this study will be publicly available and can be used for additional subsurface studies in other regions of the WCSB and the Slave Province.

This research builds upon previous studies that focused on the shallow sedimentary sequence (<730 m) (Rajaobelison et al., 2024, In press) by extending the assessment to the deeper Precambrian basement, further demonstrating how oil and gas exploration data can be used for early stage deep geothermal resource assessment.

Thermal conductivity values significantly influence the geothermal gradient. Precambrian basement rocks exhibit higher thermal conductivity than sedimentary rocks, resulting in a slower temperature increase within the basement. In contrast, the sedimentary sequence, with its lower effective thermal conductivity, act as a ‘thermal blanket’, trapping heat and causing a higher temperature increase with depth.

Our findings indicate that the highest geothermal gradient is expected below Hay River, with temperature increasing more rapidly than in other communities. Conversely, Kakisa has the lowest geothermal gradient, followed closely by Enterprise. The variation in subsurface temperature among these communities, despite their proximity within a 120 km radius, highlights the importance of localized resource assessments rather than relying on extrapolated values from a regional scale assessment.

Temperature at depth for Hay River and Fort Providence reveal a similar profile within the sedimentary sequence, but is significantly different in the Precambrian basement. This disparity can be explained by a lower thermal conductivity and a higher heat flux inside the Slave Craton for Hay River. These factors contribute to a faster increase in temperatures at depth. Similar observations can be made for Enterprise and Kakisa.

Although we would have expected similar temperature due to their proximity, Hay River and Enterprise (approximately 30 km apart and part of the same tectonic domain) show a notable temperature difference at depth. This discrepancy is primarily due to the different heat flow values used in calculations and originating from well temperature measurements that can enclose a high uncertainty (Rajaobelison et al., 2024).

Upon comparing our findings with those of other studies (Grasby et al., 2011; Majorowicz & Grasby, 2010b, 2010a), notable disparities in temperature estimations emerge, particularly in Hay River. Majorowicz & Grasby (2010b) estimate a temperature of approximately 85 °C at 3 km and around 250 °C at 10 km for Hay River. On the other hand, we estimate temperatures slightly above 150 °C at 3 km and 500 °C at 10 km. Moreover, Grasby et al. (2011) report a depth of 3.5 km to reach 150 °C in that region. Also, Majorowicz & Grasby (2010a) estimate a temperature slightly below 350 °C at 10 km for the community locations. However, the temperatures we calculated at depth in Hay River and Fort Providence are much higher than those reported in previous studies. Enterprise and Kakisa values are also higher albeit slightly lower than the other two communities. This is mostly attributed to the utilization of a larger heat flow estimate in our calculations. For example, when using a lower heat flow value, similar to these studies, 95 ± 5 mW m^{-2}, our results align more closely with those of previous studies.

Input temperature is the most influential factor in the estimation of the geothermal gradient and heat flow; therefore, its variability directly affects the results. Noisy or poor-quality data can significantly bias geothermal gradient assessments. The reliability and accuracy of temperature measurements can be influenced by factors such as the method of measurement, quality, depth, season, and the age of the data, as discussed by Majorowicz et al. (1999, 2014b). In this region, the availability of high-quality thermal data is limited, with most drilling reports dating from the 1960s to the 1980s. Also, wells are limited in depth, with only four boreholes exceeding 1000 m and situated at a reasonable distance (<50 km) from the communities. Reconsidering the input values, particularly for unusually high heat flows such as those observed in Hay River and Fort Providence, which may have been overestimated, could lead to more consistent results between communities and with literature values.

Another limitation of the study is that the 1D analytical temperature models do not account for expected decreases in thermal conductivity with increasing temperature and pressure at depth (Clauser, 2011; J. Majorowicz, Nieuwenhuis, et al., 2014). These factors could influence the values obtained by increasing our temperature values at greater depths, especially those predicted to 10 km. Additionally, our results are theoretical predictions that should be interpreted with caution. They heavily depend on the inputs used in calculations, and the uncertainty increases with depth, as highlighted by the optimistic and pessimistic scenarios and in comparison to the literature.

This study is not intended as a regional or large-scale analysis and does not evaluate three-dimensional resource distribution. It does not focus on potential aquifers or consider structural geology impacts, such as faults and fractured patterns on localized resources.

However, one of the strengths of our study is the use of representative thermal properties for the geological formations under the communities. These were obtained from laboratory measurements on the same geological formation rocks that we expect to be found below the communities, rather than from broad literature values, as was done in previous studies. Furthermore, our localized approach ensures relevance to community end users, making our findings directly applicable and reliable for the community's geothermal resource assessment.

Geothermal resources within the sedimentary sequence (<37 °C) could be used for heating applications, most likely requiring the use of a heat pump system. However, for applications requiring temperatures above 40 °C, which can support a wide range of geothermal energy uses, drilling into the Precambrian basement would be necessary to reach such temperature. Specific applications, such as electricity production, necessitate temperatures above 80°C, below which it becomes uneconomical. However, a high temperature above 150°C is more commonly employed for power generation (Ahmadi et al., 2020). Based on our 1D models, such temperature is expected at depths about 1500 m and 3000 m for the community of Hay River and around 2250 m and 4500 m for Kakisa. Low permeability crystalline rocks are expected at such depth, which would either require EGS or DBHE.

While our results indicate a great geothermal potential for the South Slave communities, with high temperature at depth, these are theoretical estimates. This potential can only be validated through exploration drilling to confirm the geothermal potential.

6. Conclusions

This study provides critical insights into the thermal properties of the Precambrian basement rocks beneath the sedimentary basin in the South Slave communities of the NWT. It was combined with previous temperature assessment in the sedimentary rock cover.

The calculated temperature profiles highlight the importance of local resource assessments for the community's end user, from which geothermal development could potentially contribute to energy independence, reduce greenhouse gas emissions, and promote regional economic development.

The temperature profiles presented in this work can be used as input for future work, focusing on numerical simulations aimed at evaluating the efficiency of heat extraction for each community considering DBHE. Such systems, when coupled with heat pumps, present a promising technology for heating applications in the South Slave Region. Numerical modelling will further assist in defining the thermal output of these systems in locations without deep aquifers. These efforts will provide important information for future decision-making about energy supply in that region as well as any further geoscience study in the area.

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