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Curie Point Depths and Heat Production in Yukon, Canada

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ABSTRACT

Recent research provides an expanded understanding of the thermal state of the crust and the potential for geothermal energy resources in Yukon, Canada. This paper presents an overview of heat flow, Curie point depth mapping, crustal-scale thermal modelling, and new heat generation data which all suggest that south-central Yukon is characterized by relatively higher temperatures in the mid- to shallow crust compared to the northern and southeastern portions of the territory. Heat flow data in Yukon are sparse, but previous measurements show anomalously high heat flow values in the Yukon portion of the northern Canadian Cordillera (i.e. south-central Yukon) having values as high as 105±22 mW/m^2. This compares with an average heat flow for all of Canada of 64±16 mW/m^2. Curie point depth (CPD) mapping is a technique which estimates the depth in the Earth's crust to the Curie point temperature (~580 °C) where magnetization in rocks disappears. Recent work by us and others suggests that the CPD for south-central Yukon is relatively shallow and has the range 12-27 km. These CPD results agree well with an 18-23 km depth to Curie point we estimate using a two-layer thermal model of the crust for southern Yukon. The regions with shallow CPD estimates in Yukon generally correspond to areas with elevated heat flow measurements. Geologically, the regions with shallower CPD values correspond to the Cordillera, while deeper CPD areas in the north and southeast portions of Yukon appear to be co-located with continental platform rocks of Ancestral North America that exhibit lower heat flow. In addition, a new compilation of geochemical data reveals numerous localities across southern Yukon with anomalously high values of heat production in Cretaceous and younger granitoid plutons. We assessed geochemical data from ~560 samples and calculated heat production for each sample, then mapped the results across the territory. A large number of samples yielded anomalously high heat production values of 3-10 μW/m^3. A smaller number of samples gave even higher heat production values >10 μW/m^3. This compares to a heat production value of ~2.5-2.8 μW/m^3 for typical granite. In general, Cretaceous plutons in southern Yukon show higher heat production values compared to Tertiary plutons. Overall, south-central Yukon is a large region (~250,000 km^2) which appears to be broadly characterized by elevated temperatures in both the mid- and shallow crust. In addition, anomalously high heat production measured in granitoid rocks in southern Yukon appear to be abundant and provide yet another source of heat for geothermal resources. If adequate subsurface permeability can be found in the region, relatively small, low-enthalpy geothermal reservoirs may be numerous across south-central Yukon. Two regions of potential deep crustal permeability in south-central Yukon are the Denali and the Tintina fault zones. Both are crustal-scale, strike slip faults that cut northwest across the entire Yukon territory. Successful identification and exploitation of geothermal resources in Yukon would be particularly beneficial due to the cold northern climate and could help supply heat and power to off-grid, fossil-fuel powered entities in Yukon such as mining operations and remote communities.

1. INTRODUCTION

The Yukon territory is located in the northwest corner of Canada. It has few hot springs, no active volcanism, and very limited recent volcanism, all of which might suggest a lack of viable geothermal resources. However, multiple lines of evidence suggest that the Earth's crust is relatively thin (i.e. 33-36 km) in the northern Canadian Cordillera in Yukon (Cook et al., 2004; 2012; Clowes et al., 2005; Snyder et al., 2002). This hypothesis is supported by anomalously high heat flow measurements scattered across Yukon having a value of 105±22 mW/m^2 (Lewis et al., 2003). Such high heat flow is similar to that found in the Basin and Range province of Nevada (Blackwell et al., 2011) where geothermal resources are abundant. Thus, if elevated heat flow is widespread in southern Yukon and if sufficient permeability exists in the subsurface, a significant number of geothermal reservoirs located at drillable depths may be present in Yukon.

At present, hydropower, diesel, and liquefied natural gas (LNG) provide electricity to most of the larger cities and towns in Yukon. Smaller, off-grid communities depend exclusively on diesel and LNG power generation and transporting fossil fuels to this corner of

Canada is expensive. For these reasons, and due to the cold climate, a locally-derived source of heat and power, such as geothermal energy, would be of value to Yukon residents and the economy. This paper briefly reviews recent research on heat flow, Curie point depth mapping, crustal-scale thermal modelling, and heat generation in Yukon. The combined geoscience data paints a picture of elevated heat flow across a broad swath of south-central Yukon within the northern Canadian Cordillera with potential for direct use, and possibly, electricity generation from geothermal resources. A geothermal-focused, scientific drilling program, spearheaded by the Yukon Geological Survey, has been underway since 2017 at two separate localities to acquire more information about geology, heat flow, temperature gradients, and permeability in the subsurface.

2. HEAT FLOW

Heat flow data in Yukon are sparse. The data are primarily derived from oil & gas wells in the northern and southeastern parts of Yukon, and mineral exploration holes in the south-central part of the territory (Figure 1). As far as the authors are aware, there have been no new, published heat flow measurements in Yukon for ~15 years. In general, heat flow trends in Yukon show lower values in the north and southeast (< 70 mW/m^2) and higher heat flow across south-central Yukon (> 80 mW/m^2). Lewis et al. (2003) provided evidence that heat flow in the northern Canadian Cordillera (north of 59 °N) is 105±22 mW/m^2. For comparison, the average heat flow for all of Canada is 64±16 mW/m^2 (Grasby et al., 2012). Due to the large parts of Yukon having no heat flow data, complementary techniques, such as Curie point depth mapping, that have broad spatial coverage could fill in gaps to help us better understand heat flow variations across the territory.

3. CURIE POINT DEPTH MAPPING

Curie point depth (CPD) mapping is a methodology, originally developed in the 1970's, which utilizes regional-scale aeromagnetic survey data to map the depth in the Earth's crust to the Curie point temperature (~580 °C) where magnetization in rocks disappears. CPD mapping has been used in combination with other methods (such as heat flow measurements) in many parts of the world as a regional scale geothermal prospecting tool. One advantage of CPD mapping is it can provide information on crustal temperatures at depths not accessible by other means (Okubo et al., 1985). Examples of previous CPD studies include regional and/or country-wide compilations in the USA, Indonesia, Japan, Turkey, Mexico, Afghanistan, Venezuela, Egypt, South Africa, Germany, and Taiwan (Arnaiz-Rodriguez and Orihuela, 2013; Aydin et al., 2005; Bansal et al., 2011; Bilim et al., 2016; Bouligand et al., 2009; Campos-Enriquez et al., 1990; Hseih et al., 2014; Manea and Manea, 2011; Nyabeze and Gwavava, 2016; Okubo et al., 1985; 1989; Saada, 2016; Saibi et al., 2015; Tanaka et al., 1999). Regions found to have shallow Curie point depths are expected to have higher heat flow, higher average temperature gradient, and, therefore, a higher likelihood of geothermal energy resources that are accessible via drilling. The CPD mapping method is particularly suited for Yukon because of the availability of public domain magnetic survey data that covers most of the territory.

Two separate groups recently performed CPD mapping that covers the Yukon territory (Witter and Miller, 2017; Li et al., 2017). Witter and Miller (2017) applied the CPD methodology of Tanaka et al. (1999) to public domain magnetic data obtained from Natural Resources Canada (http://gdr.agg.nrcan.gc.ca/). The CPD map generated by Witter and Miller (2017) is shown in Figure 2. The Tanaka et al. (1999) method assumes that long wavelength magnetic anomalies are related to large-sized magnetic sources that have a random and uncorrelated distribution within the Earth's crust. The bottoms of these magnetic sources are assumed to correspond to the ~580 °C Curie Point temperature. Curie point depth estimates for Yukon derived by Witter and Miller (2017) range from 25-54 km. The deepest CPD values (i.e. > 33 km) are located north of ~64° N latitude. The southeast corner of Yukon is also inferred to have CPD values > 33 km. By contrast, south-central Yukon shows a broad plateau with shallower CPD values of 25 – 30 km.

The study by Li et al. (2017) calculated Curie point depths for the entire Earth. They employed a CPD calculation methodology similar to Bouligand et al. (2009) and applied it to a global magnetic dataset (EMAG2; Maus et al., 2009). The CPD methodology used by Li et al. (2017) assumes a fractal magnetization of the crust. Many researchers argue that fractal magnetization is a more geologically realistic assumption for the Earth's crust (e.g. Pilkington and Todoeschuck, 1993; Maus et al., 1997; Pilkington et al., 2006; Bouligand et al., 2009; Bansal et al., 2011; Chopping and Kennett, 2015) and may yield more accurate CPD estimates compared to the assumption of random/uncorrelated magnetization. The Yukon portion of the Li et al. (2017) global CPD map is shown in Figure 3. Curie point depth estimates for Yukon derived by Li et al. (2017) range from 12 – 40 km. The deepest CPD values (i.e. > 27 km) are located north of ~64° N latitude. CPD estimates for the southeast corner of Yukon also have CPD values > 27 km. By contrast, south-central Yukon consists of a broad plateau with shallower CPD values of 12 – 27 km.

The Yukon CPD maps by Witter and Miller (2017) and Li et al. (2017) have some similarities and some differences. Qualitatively, both maps are similar in that the south-central portion of Yukon exhibits shallow CPD while the far north and SE corners of the territory show much deeper CPD values. Significant differences lie in the magnitude of the CPD values predicted by each study at a given location. For example, Witter and Miller (2017) estimate a much deeper (25 – 30 km) CPD for south-central Yukon while the Li et al. (2017) result is much shallower (12 – 27 km) for the same area. This observation is consistent with the findings of other workers (e.g. Bouligand et al., 2009) that choosing the assumption of fractal magnetization in the crust (like in Li et al., 2017) tends to make CPD estimates shallower compared to an assumption of random/uncorrelated magnetization (used in Witter and Miller, 2017). In the next section, we present the results of thermal modelling to independently predict the depth to the Curie point and ascertain which of the two CPD maps may be more appropriate for Yukon.

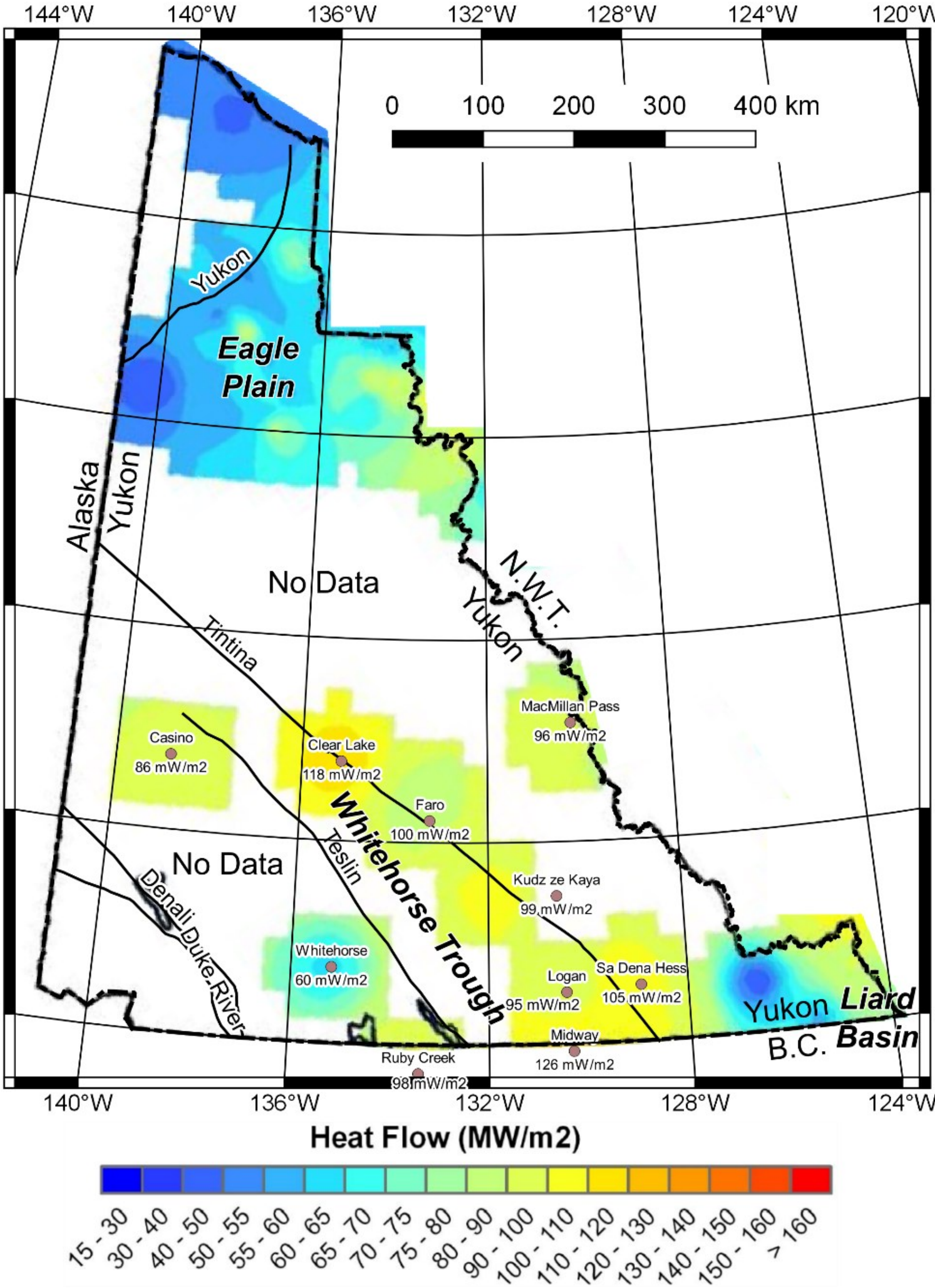

Figure 1: Heat flow map of Yukon from Grasby et al. (2012). Warm colours represent high heat flow and cool colours, low heat flow. Selected heat flow data points from Lewis et al. (2003) are also shown as brown dots labelled with the location and heat flow value. Portions of central and southern Yukon show elevated heat flow compared to other parts of Yukon.

Much of the territory lacks heat flow measurements. Black lines depict major faults (Colpron and Nelson, 2011). The locations of major sedimentary basins in Yukon are labeled in bold italics. Map is in Yukon Albers NAD83.

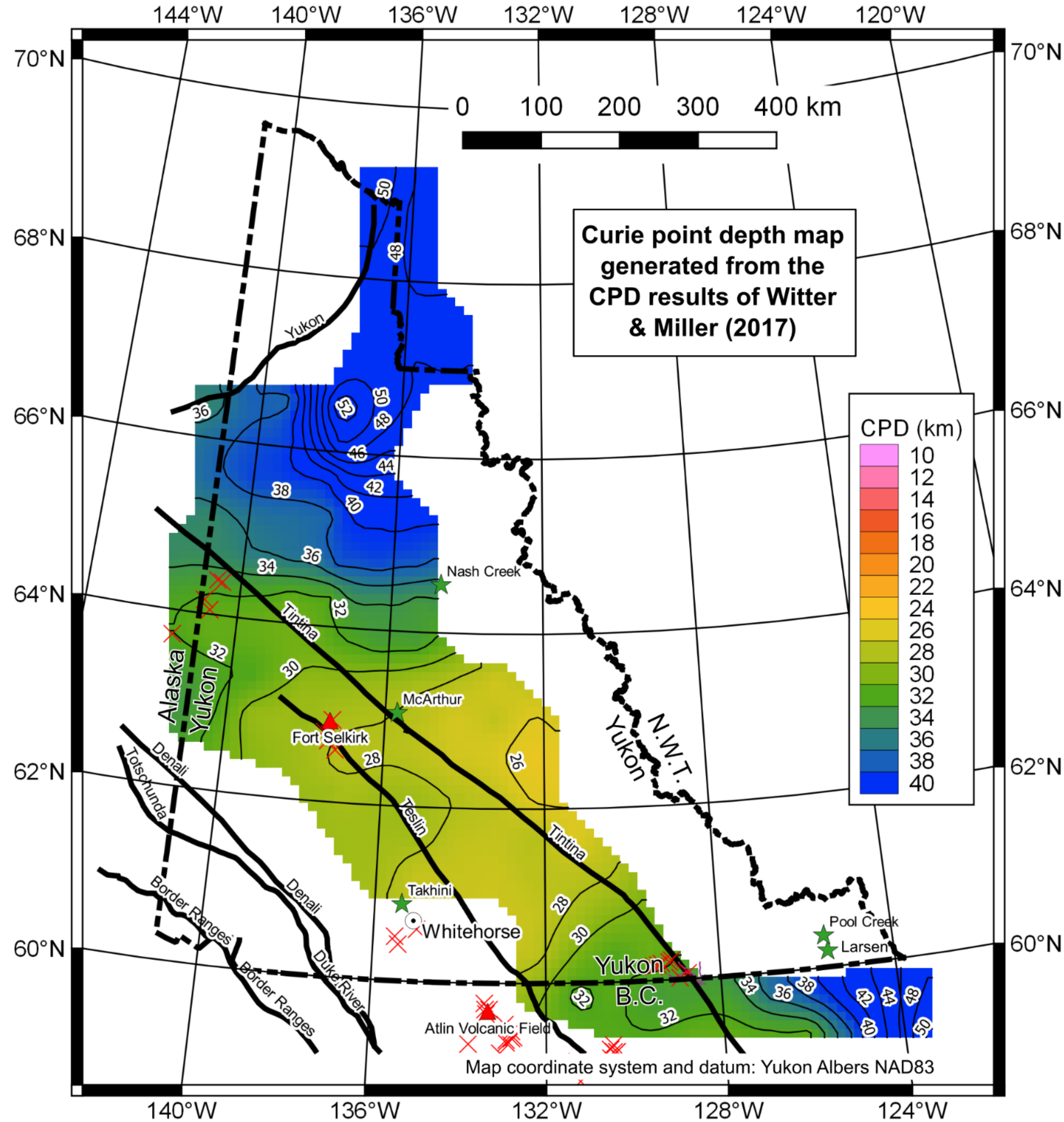

Figure 2: Curie point depth map for Yukon from Witter and Miller (2017) which uses the Tanaka et al. (1999) method and assumes random/uncorrelated crustal magnetization. Warm and cool colours represent shallow and deep CPD estimates, respectively. Contour lines show CPD in units of kilometres below the surface at 2 km depth intervals. Due to magnetic data gaps and large CPD calculation windows, Witter and Miller (2017) were not able to completely cover Yukon with CPD data points. Hot springs are shown by green stars and labeled. Red triangles denote Holocene volcanic eruptions (Smithsonian, 2016); red crosses identify Neogene and younger volcanic rocks (Edwards and Russell, 2000; Abraham et al., 2005). Black lines depict major faults (Colpron and Nelson, 2011).

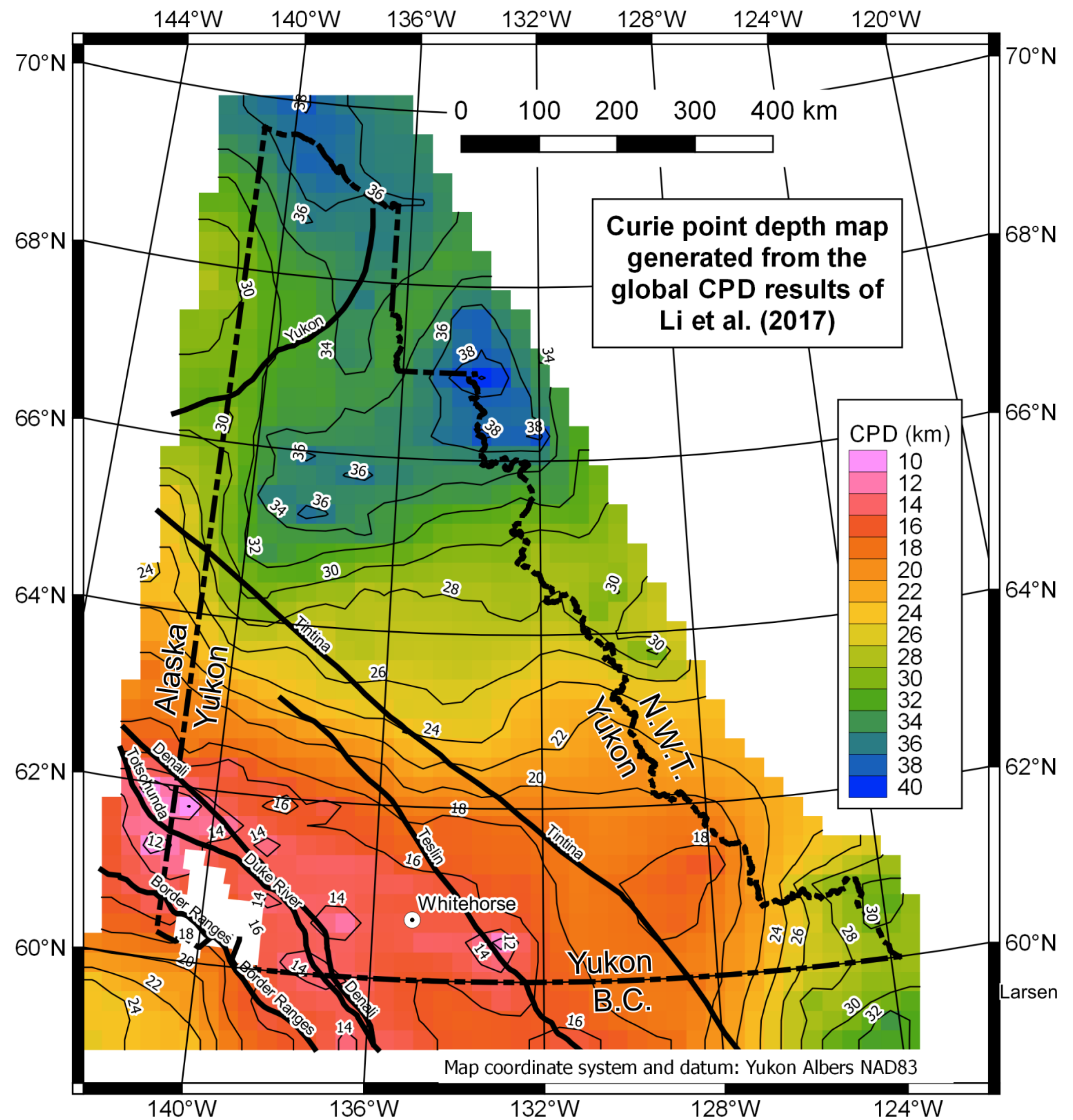

Figure 3: Curie point depth map for Yukon from Li et al. (2017) which assumes fractal crustal magnetization. Warm and cool colours represent shallow and deep CPD estimates, respectively. Contour lines show CPD in units of kilometres below the surface at 2 km depth intervals. Black lines depict major faults (Colpron and Nelson, 2011).

4. THERMAL MODELLING

Over the past 15 years, several studies have investigated the thermal structure of the crust in the northern Canadian Cordillera. For example, seismic velocity data from the SNORCLE project (Clowes et al., 2005) suggest temperatures at the base of the crust of 800-1000 °C. Based upon a crustal heat flow model, Lewis et al. (2003) predict temperatures of 950±150 °C at the base of the crust north of 59° N. Similarly, Harder and Russell (2005) used geothermometry of mantle xenoliths to estimate a temperature of 800-850 °C at the base of the crust beneath northernmost British Columbia near Atlin. A similar study of mantle xenoliths by Edwards and Russell (2000) suggests upper mantle temperatures of 950-1000 °C beneath the Fort Selkirk and Alligator Lake volcanic fields in Yukon (these may not represent the temperature at the base of the crust, but more likely represent uppermost mantle temperatures).

Taken together, the results of seismic, heat flow, and petrologic studies suggest the temperature at the base of the crust in the northern Cordillera is on the order of ~900 °C with an average crustal-scale geothermal gradient of 25-27 °C/km (calculated using a crustal thickness of 33-36 km; Cook et al., 2012).

The CPD mapping results of Witter and Miller (2017) identify a broad region of moderate CPD values (25-30 km) in south-central Yukon. These CPD values imply an average geothermal gradient of ~19-23 °C/km. Using an average crustal thickness of 33-36 km (Cook et al., 2012) for this area gives a temperature at the base of the crust of only ~625-825 °C. This is much lower than the base-of-crust temperature estimate from seismic, heat flow, and petrologic studies. Thus, the CPD predictions of Witter and Miller (2017) appear to be too deep.

In contrast, the CPD mapping results of Li et al. (2017) for south-central Yukon are much shallower having the range 12-27 km. These depths suggest an average geothermal gradient of ~21-48 °C/km which implies a base-of-crust temperature range of ~700 °C to >1000 °C. Such a temperature range overlaps well with the independent base-of-crust temperature estimates derived from seismic, heat flow, and petrologic studies (i.e. ~900 °C).

In order to further explore the thermal structure of the crust in the northern Canadian Cordillera, Witter and Miller (2017) constructed a two-layer thermal model for the crust (Figure 4) which mimics the crustal scale geology for the region (e.g. Snyder et al., 2002; Cook et al., 2004). Specifically, the thermal model consists of an upper layer ~5 km thick (Paleozoic and younger rocks consisting of displaced terranes) underlain by a ~30 km thick layer of Proterozoic metasedimentary rocks of Ancestral North America. Witter and Miller (2017) utilize a steady-state conductive temperature model for a one-dimensional crustal lithosphere (Harder and Russell, 2005; Majorowicz and Grasby, 2010):

$$Q = Q_r + D\,A \tag{1}$$

$$T(z) = T_0 + Q_r\, z\, K^{-1} + A\, D^2\, K^{-1}\, (1 - \exp(-z / D)) \tag{2}$$

where Q is heat flow at the top of a crustal layer; Q_r = reduced heat flow at the base of a crustal layer; D = thickness of the crustal layer, A = heat generation in a crustal layer, T(z) is the temperature in the crustal layer as a function of depth, z = depth, T_0 = temperature at the top of a crustal layer, and K = thermal conductivity of a crustal layer. Estimates for values of thermal conductivity, heat generation, heat flow, and temperature at the base of the crust (T_{Moho}) were derived from the literature (Table 1). There is uncertainty in the most appropriate values of K, A, and Q to assign as bulk values for the two layers of the model. Therefore, we used average values and fixed the temperature of the land surface to 0 °C (average annual temperature of Whitehorse).

The crustal-scale thermal model suggests that the Curie point (580 °C) is reached at ~20 km (Figure 4). Allowing for various values of K, A, and Q, while still attaining the expected Moho temperature range of 800 – 1000 °C, suggests the Curie point depth may range from 18-23 km (see Figure 4). Reaching the Curie point at such depths implies an average, linear temperature gradient of ~25-32 °C/km between the surface and the mid-to-lower crust. If this thermal model is accurate, then the CPD values obtained in Li et al. (2017) (i.e. 12-27 km) may also be accurate for south-central Yukon. This also implies that an assumption of fractal magnetization in the crust may be the better assumption for CPD calculations applied to Yukon.

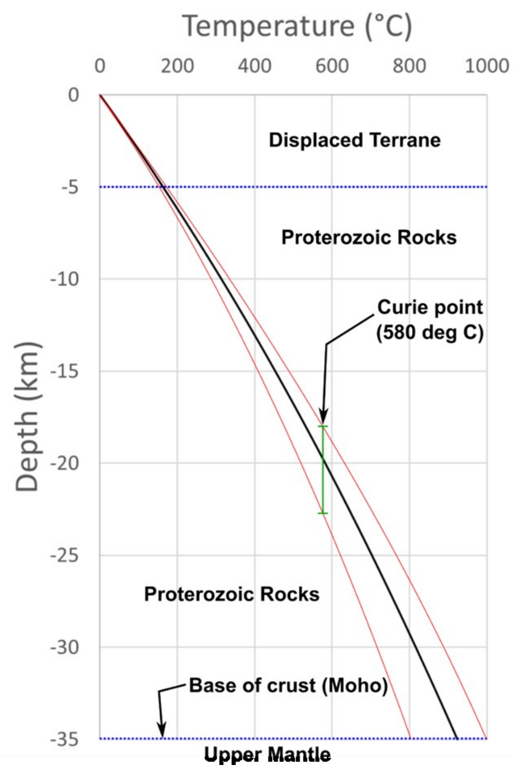

Figure 4: Two-layer thermal model constructed for south-central Yukon. The geotherm calculated in this study (black line) uses the values in Table 1 and predicts a Curie point depth of ~20 km. Approximate bounding geotherms (red lines) to reach 800 °C and 1000 °C at the base of the crust suggest a range in Curie point depth of 18-23 km. See text for further explanation.

Displaced Terrane layer (0 - 5 km)

Variable	Value	Range	Units	Description	Reference
T_{surf}	0	n/a	°C	Temperature at land surface	assumed
Q_{surf}	105	105 ± 22	mW/m^2	Heat flow at land surface	Lewis et al. (2003)
$K_{terrane}$	3	2.6-3.4	W/m.K	Thermal conductivity in displaced terrane	Majorowicz and Grasby (2010); Lewis et al. (2003)
$A_{terrane}$	4	2.0-5.0	µW/m^3	Heat generation in displaced terrane	Majorowicz and Grasby (2010); Lewis et al. (2003)
$D_{terrane}$	5	?	km	Thickness of displaced terrane	Snyder et al. (2002); Cook et al. (2004)
$Q_{terrane}$	85	n/a	mW/m^2	Heat flow at base of displaced terrane	Calculated in this study

Proterozoic Ancestral North America layer (5 - 35 km)

Variable	Value	Range	Units	Description	
T_{PROT}	163	n/a	°C	Temperature at top of Proterozoic rocks	Calculated in this study
K_{PROT}	2.7	1.8-3.4	W/m.K	Thermal conductivity of Proterozoic rocks	Majorowicz and Grasby (2010); Lewis et al. (2003)
A_{PROT}	1.5	0.9-3.7	µW/m^3	Heat generation of Proterozoic rocks	Majorowicz and Grasby (2010); Lewis et al. (2003)
D_{PROT}	30	?	km	Thickness of Proterozoic rocks	Snyder et al. (2002); Cook et al. (2004)
Q_r	40	?	mW/m^2	Reduced heat flow at base of crust	Harder and Russell (2005)
T_{Moho}	924	800-1000	°C	Temperature at base of crust	Calculated in this study; Clowes et al. (2005); Lewis et al. (2003)

Table 1: List of variables used in the two-layer thermal model. The column marked 'Value' is the average assumed values used to calculate the black line in Figure 4. The column labeled 'Range' lists the variation in these variables found in the literature. PROT = Proterozoic metasedimentary rocks of Ancestral North America.

5. COMPARISON WITH REGIONAL GEOLOGY

A comparison between the CPD map of Li et al. (2017) and the regional geology of the Yukon can further explore the relationships between our preferred thermal interpretation of the crust and large-scale structures and terrane boundaries in Yukon (Figure 5). Yukon consists of a variety of crustal blocks broken by major fault zones. In general, Yukon can be divided into the Arctic Alaska terrane (far northwest corner of Yukon), Ancestral North America (northeast of the Tintina Fault), and an assortment of displaced terranes (located mostly southwest of the Tintina Fault). Variations in CPD values across Yukon do not appear to have a one-to-one spatial association with these three geologic domains (see Figure 5).

Significant northwest-trending faults are also found in Yukon (e.g. Tintina, Teslin, and Denali). The distribution of CPD estimates do not have a consistent relationship with the major fault zones. For example, the broad region of shallow CPD values (12-27 km) in south-central Yukon extends across both the Tintina and Teslin fault zones. In contrast, the shallowest CPD estimates in Yukon mostly occur along the Denali fault zone.

The transition to deep CPD values observed in Yukon appears to coincide with the transition from deep water facies to platform facies in rocks belonging to Ancestral North America. The clearest example of this occurs at ~65 °N where CPD values drop below 28 km going northward. At about this latitude, rocks transition from deep water Selwyn Basin facies, in the south, to shelf facies of the Ogilvie Platform (a.k.a. Yukon Stable Block) in the north (Nelson et al., 2013). A second example of this relationship can be identified in the southeast corner of Yukon where the transition to deep (> 28 km) CPD values corresponds with the transition from Selwyn Basin facies (to the northwest) and shelf facies of the MacDonald platform (to the southeast; Figure 5). Regions with deeper CPD values suggest lower heat flow from the mid-to-lower crust. Thus, deep CPD values that correlate with Ancestral North American platform rocks may imply that: a) the platforms are composed of thicker, colder lithosphere and/or b) the crust in the platforms contains lower concentrations of radioactive, heat-generating elements. Either of these options would result in lower heat flow in the mid-to-lower crust, consistent with deep CPD values.

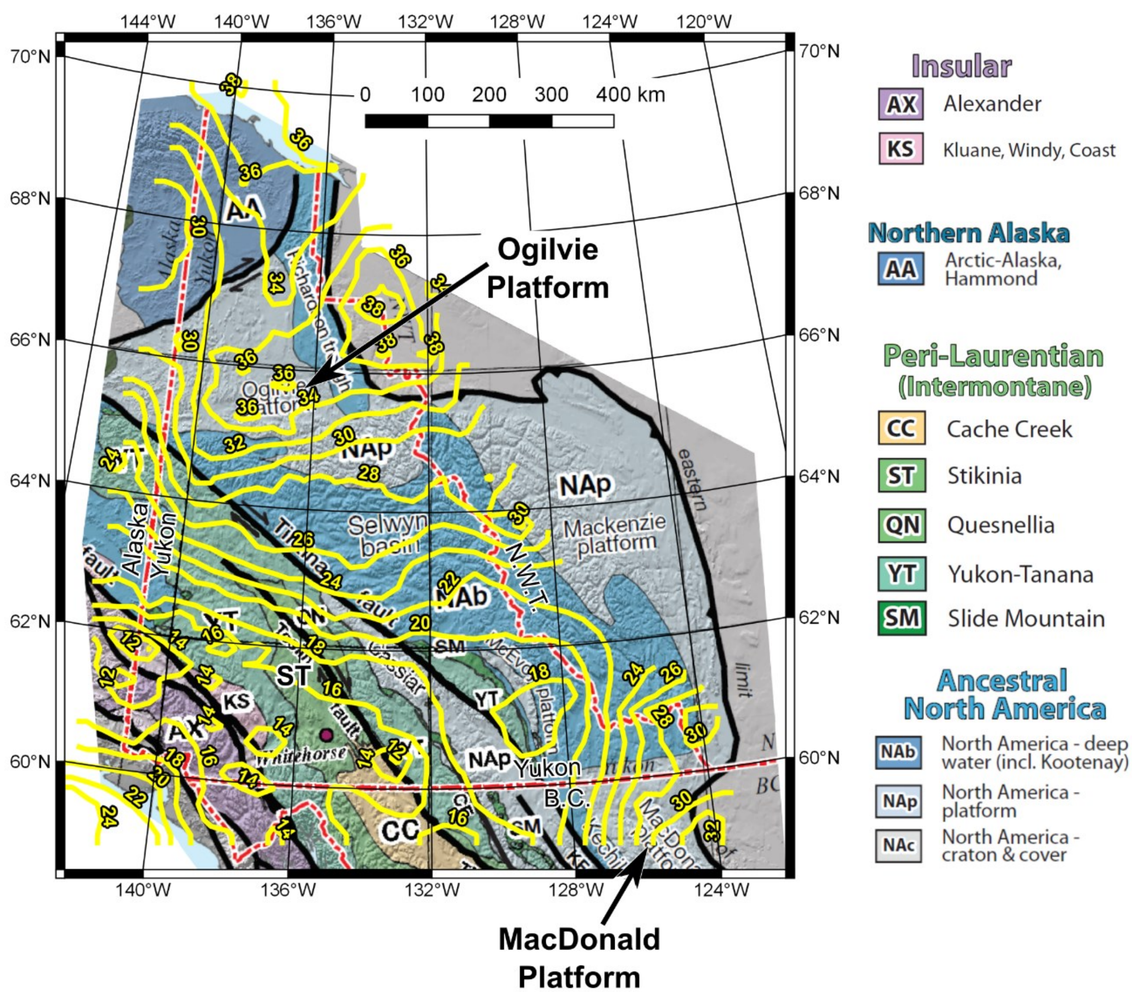

Figure 5: Comparison between the regional geologic terrane map for Yukon (adapted from Nelson et al., 2013) and the CPD map generated by Li et al. (2017). The CPD contours are shown as yellow lines and labelled with yellow numbers showing depth in km. See text for discussion.

6. HEAT GENERATION

Friend and Colpron (2017) recently compiled lithogeochemical data from Cretaceous and younger granitoid plutons and volcanic rocks to evaluate heat generation in rocks across southern Yukon. Rock samples included in this compilation cover an area of ~350,000 km^2 extending from the Yukon-British Columbia border to the Ogilvie Mountains of north-central Yukon. Heat generation was calculated for ~560 rock samples using the method of Rybach (1981) and existing geochemical data in the Yukon Geological Survey (YGS) archives. Results of the analysis reveal numerous localities with anomalously high values of heat generation in Cretaceous and younger granitoid plutons. Specifically, the southern Yukon data compilation yielded 263 samples with anomalously high heat generation values of 3-10 $\mu W/m^3$. A smaller number of samples (25) gave even higher heat generation values >10 $\mu W/m^3$. For comparison, typical granite has a heat generation value of ~2.5-2.8 $\mu W/m^3$ (Hasterok and Webb, 2017). In general, Cretaceous plutons in southern Yukon show higher average heat generation values (average ~4.9 $\mu W/m^3$; n=484) compared to Tertiary plutons (average ~2.0 $\mu W/m^3$; n =47). This observation is somewhat unexpected since older rocks have more time to undergo radioactive decay and lose their heat generation potential. Regardless, the observations of Friend and Colpron (2017) are clear that the older plutons in Yukon exhibit higher heat generation compared to younger plutons. Regional bedrock mapping shows that Cretaceous plutons are relatively abundant and spread widely in southern Yukon (e.g., Colpron et al., 2016). Therefore, elevated heat generation values observed in Cretaceous plutons likely have a significant influence on radioactive heat generation in the shallow crust for much of southern Yukon. The anomalously high heat generation values calculated for southern Yukon also provide supporting evidence for the ~4 $\mu W/m^3$ heat generation value assumed for the Displaced Terrane in the crustal-scale thermal model presented in Section 4.

7. DISCUSSION

This review of heat flow data, Curie point depths, crustal thickness, and heat generation in Yukon tells a consistent story that a broad region across south-central Yukon, coinciding with the northern Canadian Cordillera, is likely characterized by elevated heat flow through thin crust. This large region covering ~250,000 km^2 extends from the Alaska-Yukon border (141º W) in the west to ~127° W longitude in the east and the British Columbia-Yukon border (60º N) in the south to ~64° N latitude in the north. Characteristics of this region include: 1) sparse point measurements of heat flow with an elevated value of 105±22 mW/m^2, 2) relatively thin crust (~33-36 km), 3) relatively shallow Curie point depths (12-27 km), and 4) elevated heat generation in abundant plutons (>4 $\mu W/m^3$) at numerous locations across the territory. Collectively, this evidence suggests that the entire ~250,000 km^2 region in south-central Yukon can be expected to have heat flow values on the order of 100 mW/m^2. In addition, specific sub-regions in south-central Yukon that are in close proximity to heat generating plutons may be expected to exhibit even higher levels of crustal heat. Despite a paucity of hot springs and a lack of active volcanism in the territory (common indicators of subsurface geothermal resources), multiple lines of evidence strongly support the presence of elevated levels of heat in the crust across a large area of south-central Yukon.

Heat in the crust, however, is but one requirement for a geothermal resource to be viable. The other requirement is fractured rock in the subsurface (i.e. permeability) to allow hot geothermal fluids to flow into a wellbore and then to the surface. Two regions of potential deep crustal permeability in south-central Yukon are the Denali and the Tintina fault zones. Both are crustal-scale, strike slip faults that cut northwestwards across the entire Yukon territory. Regions of structural complexity along these fault zones (e.g. fault step-overs, intersections, accommodation zones, etc.; Faulds et al., 2013) are the most likely areas to exhibit elevated permeability. Geothermal reservoirs that may exist along the Denali and Tintina fault zones would be analogous to structurally-controlled geothermal systems in Nevada that derive their heat from deep circulation of geothermal fluids along permeable sections of the faults.

Another analog of the type of geothermal resource which is likely present (abundant?) across south-central Yukon is Chena Hot Springs in Alaska which generates 400 kW of electricity from ~75 °C geothermal fluids (Holdmann, 2007). A radiogenic pluton, which underlies the Chena Hot Springs area, likely serves as the heat source (Kolker, 2008) and permeability is apparently controlled by near-surface faults and/or lithologic contacts (Erkan et al., 2007). Radiogenic, high heat generation plutons located in Yukon may create similar geothermal reservoirs. It should also be noted that the geothermal power generating facility at Chena Hot Springs is a particularly good example of how to take advantage of the cold northern climate to generate electricity, even with relatively low geothermal fluid temperatures.

Thermal insulation provided by sedimentary rocks is another important factor that can strongly influence temperatures in the uppermost few kilometres of the crust. This topic is not addressed in this paper but should be considered in assessing the geothermal resource potential in Yukon. Regions capped by a thick succession of thermally-insulating sedimentary rocks commonly contain higher temperature geothermal fluids. The Whitehorse Trough, located in south-central Yukon is one such region containing >3 kilometers of sedimentary rocks (Figure 1). Similarly, deep sedimentary basins such as Eagle Plain (northern Yukon) and the Liard Basin (SE Yukon) may have sufficiently thick thermally-insulating cap rock to generate such warm conditions despite lower thermal input from the mid-to-lower crust as evidenced by deeper CPD values in those areas.

8. CONCLUSIONS

Two different Curie point depth mapping methods attempt to predict the depth to 580 °C across Yukon. Based upon a comparison with geothermal gradients predicted using other methods, we conclude that the CPD estimates derived from Li et al. (2017) are more accurate for Yukon. The CPD results are important because they cover the entire territory and demarcate regions where one would expect higher vs. lower average geothermal gradients in the Earth's crust (Figure 3). Thus, the Li et al. (2017) CPD map for Yukon can be used to infer average geothermal gradients in the territory when used in conjunction with existing, sparse heat flow measurements. Importantly, a broad region of south-central Yukon can be expected to have elevated geothermal gradients relative to other parts of Yukon. This region extends from ~64 °N to the Yukon-B.C. border and from ~127 °W to the Yukon-Alaska border. CPD estimates along the Denali fault zone are among the shallowest in Yukon. This, along with higher seismicity on the Denali fault zone, which could generate fractures and increase permeability, suggests it is more geothermally-prospective than the Tintina fault zone.

Recent heat generation measurements across southern Yukon also provide strong corroborating evidence for elevated levels of heat in the uppermost Yukon crust. A large database compiled for southern Yukon show that Cretaceous plutons exhibit average heat generation values nearly twice that for typical granite. These heat-generating plutons are abundant in southern Yukon and could serve as yet another source of heat for geothermal resources.

The geothermal exploration drilling program undertaken by the Yukon Geological Survey, which began in November 2017, will provide an important test to our current understanding of subsurface temperatures in the Yukon crust. Additional drilling beyond the current YGS effort will be required to confirm heat flow characteristics in various geological and structural environments in Yukon. In addition to drilling, a focused effort on the neotectonics and structural geology of the Denali, Teslin, and Tintina fault zones is needed to better understand structural controls on geothermal fluid flow and identify portions of the fault zones with the most favourable permeability conditions. Lastly, geologic and structural mapping in the vicinity of high heat generating plutons would be valuable to target permeable zones for future test drilling. Such studies would help unlock the geothermal resources of south-central Yukon and potentially provide heat and power to Yukon residents and the mining sector, an outcome which could serve to bolster the economy of the territory.

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