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Geothermal Studies in Yukon – Collaborative Efforts to Understand Ground Temperature in the Canadian North

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ABSTRACT

As part of the Canadian government's commitment to establishing clean energy in the North, the Yukon Geological Survey is collecting subsurface temperature data near communities in the southern part of the territory. The research is a collaborative effort among federal and territorial geoscientists, universities, First Nation governments, and geothermal consultants. A major goal of the project is to determine whether ground temperatures warrant further geothermal exploration in the territory. The study also presents an opportunity for Yukon Geological Survey to educate the public about geothermal energy. This paper summarizes the geothermal research conducted since 2016. In 2016-2017, existing geoscience data were compiled to determine: a) geothermal gradients and depths of thermal inversions; b) regional depths to Curie Point; c) distribution of Cretaceous and younger magmatic rocks; and d) potential heat production from gamma-radioactivity in those granites. In 2017, a 500 m temperature gradient well was drilled in the Whitehorse area, near Takhini Hot Springs, where surface water is 46°C. In 2018, a temperature gradient well was drilled to 497 m in the Tintina fault system, near Ross River. Results to date suggest further drilling in the Takhini Hot Springs area is warranted to better characterize ground temperature below 500 m depth, and that further exploration along the Tintina fault near Faro is warranted. The regional compilations have identified a number of areas where temperature gradient wells should be considered.

1. Introduction

Adjacent to the 'Pacific Ring of Fire', the Yukon Territory in northwestern Canada is a prime candidate for geothermal energy. Major geological features, such as the Tintina and Denali faults, abundant plutonic rocks, extensive sedimentary rock cover, and numerous hot springs all suggest the possibility of elevated geothermal heat. Previous studies of heat flow and geothermal potential in Yukon relied primarily on sparse and incomplete geoscience data. In 2016, the Yukon Geological Survey initiated a geothermal research project that aims to model areas of high heat flow using existing geological, geochemical and geophysical data, and enhance existing subsurface temperature data by drilling targeted, slimhole temperature gradient (TG) wells in specific geological settings. Primary funding for the project is from the Government of Canada (Canadian Northern Economic Development Agency's Strategic Initiatives in Northern Economic Development (SINED) Fund) and Yukon Government. Research partners include the Geological Survey of Canada, University of Alberta, Innovate Geothermal Ltd, Ta'an Kwäch'än Council, and Ross River Dena Council (RRDC). This paper describes the current status of geothermal research in Yukon. A series of geothermal gradient and depth of temperature inversion data is compiled and presented here from pre-existing geoscience data. Recent and/or new data presented include regional Curie Point mapping, distribution of potential radiogenic heat production from Cretaceous and Cenozoic granites, and preliminary heat flow results from two 500 m TG wells. The study aligns with Canada's interest in reducing remote northern communites' reliance on hydrocarbons for power and heat. Providing baseline geothermal data, and targeting areas of higher heat flow, will reduce geothermal exploration risk in Yukon and potentially drive a shift to development of local clean energy supplies to support remote northern communities.

2. Background

2.1 Location and energy supply

The Yukon Territory is in northwestern Canada, north of the Province of British Columbia and east of the State of Alaska (Fig. 1). It has a total land area of 482, 443 km^2, population of 35,874, and a population density of 0.1 persons per square kilometer (Statistics Canada, 2016). Approximately 73% of the population (~25,000 people) live in the territory's capital, Whitehorse, in the south-central part of the territory. The other ~27% are in communities of <1400 people, mostly in the southern half of the territory.

In contrast to the United States, which is the world's biggest producer of geothermal power, Canada generates no electricity from geothermal energy, although there is some direct usage for district heating (Raymond et al., 2015). In Yukon, over 95% of the territory's power is currently produced by hydro-generating stations and distributed to most communities, making Yukon one of Canada's leaders in "green" energy (Yukon Energy, 2018). However, Yukon's population is growing rapidly and its power grid is not connected to North American transmission lines. Planning for future power production has identified several potential sites for hydro development, but these have met with strong opposition from communities. Diesel and liquefied natural gas are used for back-up on Yukon's grid (particularly in cold winter months), or during peak usage times, and four Yukon communities rely solely on diesel-power generation. Yukon's power requirements are expected to grow, and Yukoners' expectations are that additional power production will be from one or more renewable sources. Given the opposition to new hydro dams, options for scalable, on-demand power are limited. Geothermal power presents an appealing possibility.

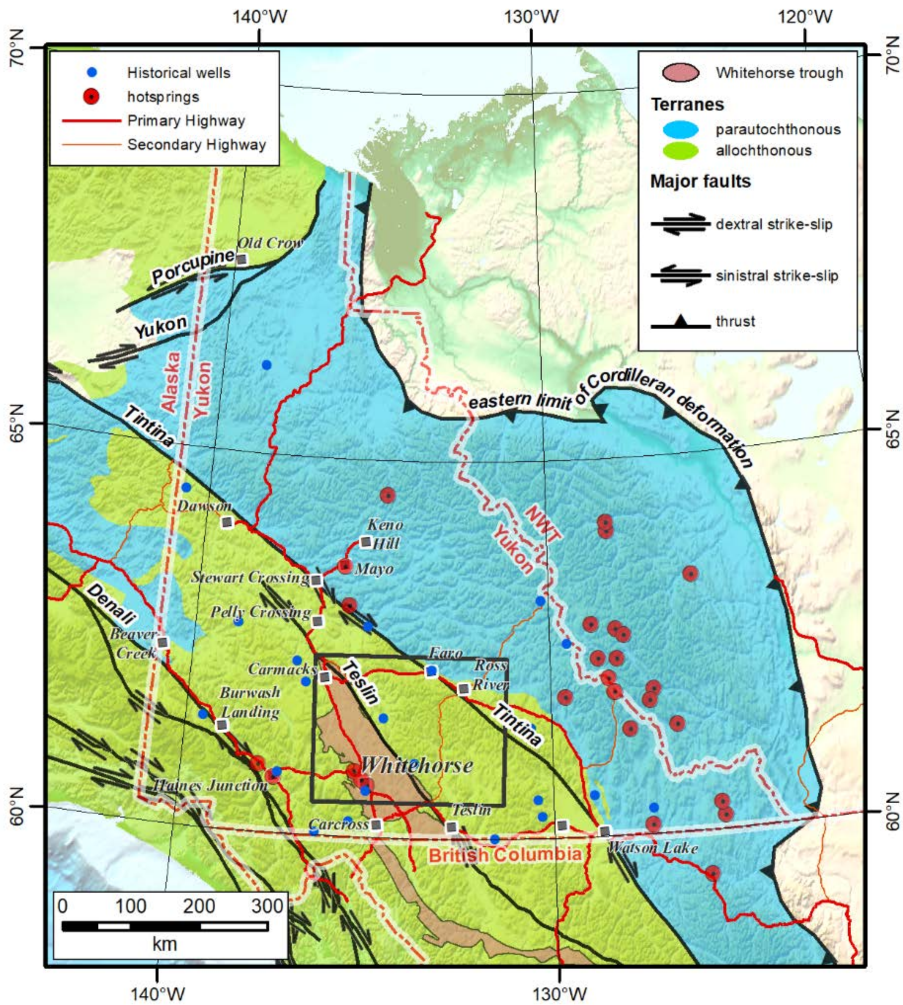

Figure 1. Simplified terrane map of Yukon showing the distribution of parautochthonous rocks of the Ancestral North American margin, allochthonous terranes of island arc and oceanic affinities, and major crustal faults. The Jurassic Whitehorse trough is shown in brown. Also indicated are the locations of known thermal springs and historical wells from which bottom temperatures were obtained. The black box indicates the area of Figure 2.

With respect to the use of geothermal energy for heat, direct use applications in Yukon are limited to low-grade systems to keep water systems from freezing as well as a hot springs resort north of Whitehorse. It is estimated that ~90% of homes are currently heated by fossils fuels (70% oil, 20% propane; C. Cottrell, pers comm. May 2018), supplemented by wood and pellet heat. All petroleum products are imported to Yukon via roads from southern provinces;

transportation of this fuel accounted for 63% (3,140 TJ) of energy used in Yukon in 2015 (Vector Research, 2017). While geothermal power production is not currently top-of-mind for Yukoners, district heating represents a significant opportunity that could see immediate reduction in greenhouse gas emissions.

2.2 Geothermal exploration in Yukon

In addition to traditional knowledge of hot spring or seep locations from Yukon First Nations (e.g. D. Irvine, pers. comm., 2017) our modern understanding of heat flow and geothermal potential in the territory began with the Government of Canada's Geothermal Energy Program (CGEP; see Jessop, 2008a and 2008b; Grasby et al., 2012), which existed between 1976 and 1986. Several Yukon-specific publications resulted from this program including thermal and mineral spring studies (Crandall and Sadlier-Brown, 1978); and temperature profile, heat flow, thermal conductivity, geothermal gradient and depth-temperature maps derived from petroleum and mineral exploration wells (e.g. Geotech Ltd., 1984; Burgess et al., 1982; Majorowicz and Morrow, 1998; Jessop et al., 1984; Majorowicz and Dietrich, 1989; Jessop et al., 2005). However, these data are sparsely distributed, mostly distal to population centers, are at variable depths, and typically only have one temperature data point (basal temperature only). Further, none of these wells were specifically drilled for geothermal exploration, and borehole temperatures likely do not reflect stabilized temperature conditions.

Since the end of CGEP, there have been additional geothermal-related studies. Grasby et al., (2000) published an analysis of thermal spring chemistry and geothermometry at Takhini Hot Springs, north of Whitehorse, as part of a larger project looking at the geochemistry of thermal springs in western Canada. They found that the Takhini Hot Springs is a carbonate-hosted spring with measured surface water temperature of 46°C, and subsurface temperatures inferred to be 116°C using the chalcedony geothermometer. The springs originate as meteroric water that circulates through the crust to obtain heat. Lewis et al. (2003) republished some of the heat flow measurements from a number of exploration wells from the CGEP program, and also added seven new measurements from Yukon mineral exploration holes. These data were used to model crustal temperatures in the Cordillera and indicate that heat flow and generation in the Canadian Cordillera north of 59°N (i.e. northern BC and Yukon) is very high (105 ± 22 mW/m^2). A series of confidential studies were commissioned for Yukon Energy Corporation (YEC; a publicly-owned electrical utility) between 2009-2013 to collect baseline technical data on potential geothermal sites near a series of hot/warm springs in the territory for the purpose of electricity generation. A published geothermal economic resource analysis by KGS Group (2016) for YEC, based on these confidential studies, concluded that there is a modest geothermal resource available for development in Yukon, with relatively low (<150°C) inferred temperatures, requiring the use of a binary geothermal power plant. However, the study recommended further geological information to adequately evaluate the resources, including drilling TG wells.

In 2012, EBA Engineering Consultants Ltd., drilled a 387 m deep water well for Government of Yukon for the Kluane First Nation. The well was drilled in the community of Burwash Landing (Fig. 1) to determine the potential of future geo-exchange applications. The well encountered 16°C water at depth, and measured a geothermal gradient of 44°C/km over the depth of the well (EBA Engineering Consultants Ltd., 2013).

In 2014, the Dena Nezziddi Development Corporation of RRDC commissioned a geothermal exploration program of the Tintina fault zone near Ross River (Fig. 1) to explore options for community heat. This study represents the most comprehensive geothermal exploration program to date in Yukon and presents integrated field-based structural analysis and mapping, with acquisition and interpretation of aeromagnetic and magnetotelluric geophysical data (Mira Geoscience, 2017). This study identified ten drilling targets, one of which was drilled as part of this current study.

In 2016, the Canadian Geothermal Energy Association (CanGEA) published geothermal favorability maps of Yukon based on compilation of existing qualitative and quantitative information about local temperature profiles, geothermal gradient, estimated conductivity, heat flow and technical and theoretical potential (CanGEA, 2016).

2.3 Geologic Setting

The North American Cordillera comprises rocks that record more than 1.8 b.y. of Earth history (Nelson et al., 2013). The rocks document the evolution of western North America from breakup of the supercontinent Rodinia (780-570 Ma) and development of the western Laurentian margin, to accretion of various allochthonous island arc and oceanic terranes beginning in the late Paleozoic (Nelson et al., 2013). Laurentian rocks underlie most of eastern Yukon (Fig. 1) and comprise Proterozoic to Triassic platformal and basinal sedimentary strata deposited along the passive margin. Allochthonous terranes occur mainly in southwest Yukon and include Paleozoic to Mesozoic volcanic, plutonic, sedimentary and metamorphic assemblages that represent magmatic arcs, microcontinents and ocean basins that developed in peri-Laurentian and Arctic realms (Nelson et al., 2013). Westward drift of North America in the Mesozoic led to accretion of these terranes, and subsequent imbrication and translation relating to development of the northern Cordilleran orogen, processes that are still active today.

2.3.1 Tintina fault

For the most part, the dividing line between Laurentian rocks to the northeast and allochthonous terranes to the southwest is the northwest-striking Tintina fault: the most prominent physiographic and geologic feature in Yukon (Fig. 1, 2). The fault, an extension of the Northern Rocky Mountain Trench fault in British Columbia, forms a topographic depression (trench) and locally controls the flow of the Yukon, Stewart, Pelly and Liard rivers. It is a steeply NE-dipping dextral strike-slip fault that has ~430 km of early Cenozoic displacement (Gabrielse et al., 2006) with mild activity still recorded today (Leonard et al., 2008). In the corridor between Ross River and Faro, the fault zone is approximately 4 to 10 km wide and consists of six prominent sub-parallel fault strands linked by a series of high-angle synthetic faults (Mira Geoscience, 2017; Yukon Geological Survey, 2018). Mapped bedrock geology in the fault zone is dominantly Carboniferous sedimentary and volcanic rocks, and Eocene volcanic, volcaniclastic and minor sediments, in many areas covered by Pleistocene glaciolfluvial and moraine deposits (Mira Geoscience, 2017; Turner, 2014).

2.3.2 Whitehorse trough

The Whitehorse trough is an elongated, northwest-trending Mesozoic sedimentary basin that extends 650 km from northern British Columbia to central Yukon (Fig. 1, 2); Colpron et al., 2015). It comprises Lower to Middle Jurassic marine to fluvial sedimentary and volcanic rocks that were deposited in a synorogenic basin developed during accretion of allochthonous island arc and oceanic terranes. Near Whitehorse, the Jurassic sedimentary rocks lie unconformably upon Upper Triassic marine sedimentary, volcanic and volcaniclastic rocks (Hart, 1997) and unconformably below Upper Jurassic to Cretaceous non-marine conglomerate and sandstone deposited in intermontane setting (Long, 2005). Middle Jurassic to Paleogene granitoid plutons intruded Whitehorse trough and older strata. Approximately 2 km west of Takhini Hot Springs, an Eocene (54 Ma; Hart, 1997) granitoid pluton intrudes Whitehorse trough and older rocks, including Upper Triassic thick-bedded limestone (Yukon Geological Survey, 2018).

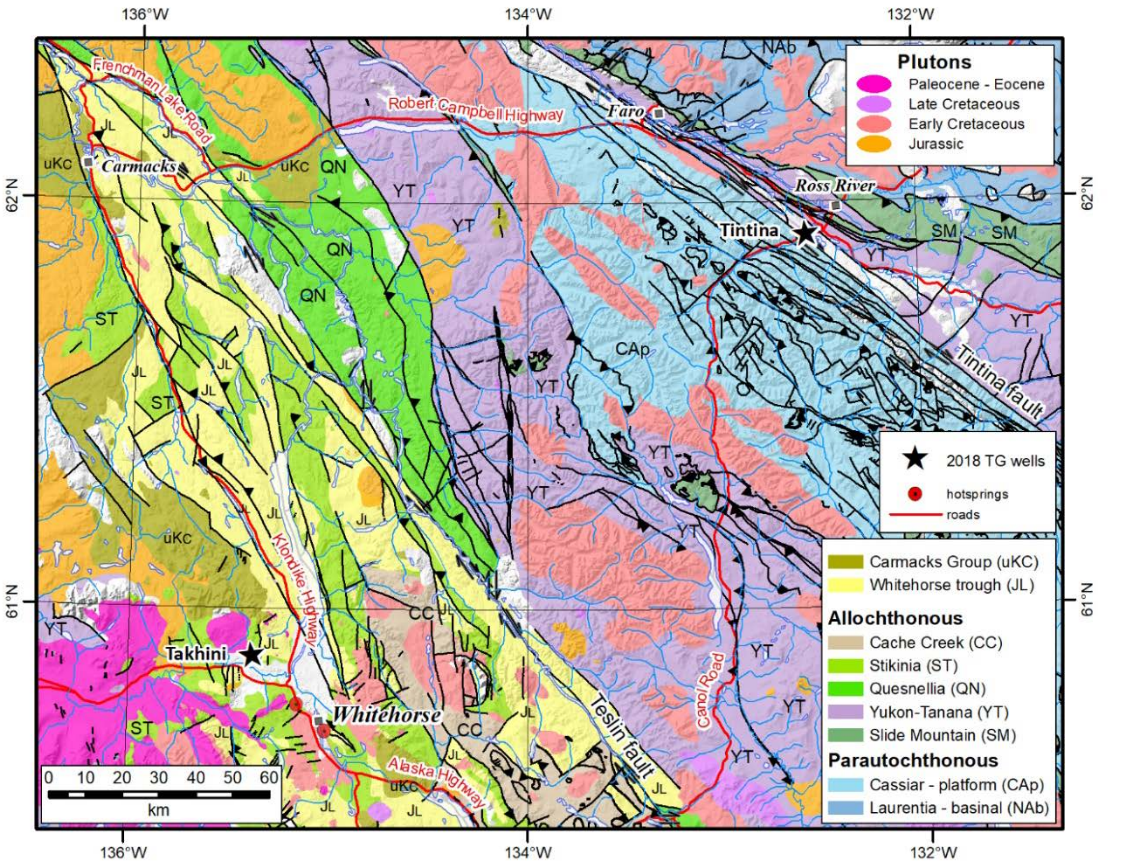

Figure 2. Simplified geological map of part of southern Yukon showing locations of the two TG wells drilled as part of this study. Geology from Yukon Geological Survey (2018).

2.3.3. Permafrost

Permafrost is ground that remains frozen for longer than two consecutive years. In southern Yukon, less than 25% of the land area is underlain by discontinuous permafrost whereas in the northern part, it is nearly continuous (90-100% coverage). Permafrost increases in thickness as you move northwards. In sporadic locations around Whitehorse, for example, it is only a few meters thick and is barely below 0°C. On Yukon’s North Slope, in contrast, it may be over 300 m thick and colder than -3°C (Yukon Geological Survey, 2014).

3. Workflow and methods

3.1 Phase 1 – Desktop studies

Two main phases defined the workflow of the geothermal exploration project. Phase I was initiated in 2016 and utilized existing geological, geochemical and geophysical data to compile regional trends in heat flow via Curie point depth mapping (CPD; Witter and Miller, 2017) and potential radiogenic heat production from granites (Friend and Colpron, 2017). The compilation of all existing data (including location of hot springs/seeps at surface, site access, distance to power lines/population) was also used to identify ~30 potential sites for TG wells in Whitehorse trough. We also compiled depth temperature profiles from 108 existing oil and gas and mineral exploration wells collected as part of the CGEP program from 1970s and 1980s wells and used to produce geothermal gradients and depths of temperature inversions for Yukon.

3.2 Phase 2 - Drilling

Phase 2 involved the drilling of two 500 m TG wells aiming at testing two potential geothermal settings in southern Yukon. The first site, near Takhini Hot Springs, approximately 30 km northwest of Whitehorse (Fig. 2), was chosen for proximity to the hot spring, the potential extension in the subsurface of a radiogenic granitoid pluton exposed ~2 km to the west, and of potential permeable limestone exposures to the east. The well site is located 2 km from the Takhini Hot Springs on Settlement lands of the Ta'an Kwächän Council First Nation who were partners in the project and contracted for drilling and thermistor installation through their Da Daghay Development Corporation. Access to the site was via an unserviced, former logging road that required minimal grading for equipment mobilization. Drilling to 500 m took 27 days between October 30 and November 26, 2017, with an average daily temperature of -12°C in Whitehorse during this period. The first 50 m was drilled with a reverse circulation (RC) drill with a 241 mm (9.5") bit. This section of the hole was cased and cemented to ensure isolation of any potential aquifers. The bottom 450 m was drilled with a diamond drill coring rig with an HQ (63.5 mm or 2.5") core barrel and a blow-out-preventer to control any pressurized fluids. Within a few days of drilling, a thermistor cable was lowered into the hole using the hoisting system of the drill rig. The thermistor string was custom designed with 16 nodes at depths of 3 and 6 m; every 10 m between 10 and 50 m; and every 50 m between 50 and 500 m from surface. The thermistor was connected to a multimeter at surface, which requires periodic manual readings. Conversion to temperature was conducted using the Steinhart and Hart (1968) equation for a 10 KΩ thermistor.

Following the Takhini well, we had initially planned for the drilling of two 600 m TG wells in Tintina Trench, near Ross River (Fig. 2), in the traditional territory of the Ross River Dena Council First Nation. In the end, technical, economic and time constraints resulted in only one well reaching a depth of 497 m, herein the 'Tintina well'. The target was determined from an analysis of 10 potential sites identified in the Mira Geoscience (2017) field mapping and geophysical study (note that the locations are not published in the report at the request of the First Nation). The TG well location is in the right-of-way of the South Canol road (km 216), in an area of structural fault complexity and near an inferred igneous intrusion interpreted from geophysical models. The site was selected to evaluate a fault-controlled geothermal system.

This phase of the drilling program was conducted in conjunction with the Ross River Dena Council and the University of Alberta, with YGS as project manager. Drilling began on February 23 and continued intermittently until March 29th (34 days). Temperatures in nearby Faro averaged -14°C during the drilling period, but at the drillsite were as low as -40°C. The original intent was to drill with an RC rig to consolidated bedrock, which in lieu of nearby well information was anticipated from surficial studies to be within 35 m of surface. At 140 m the RC rig had exceeded its depth limit and was replaced by a diamond drill. One hundred meters of PW casing (140 mm/5.5" outside diameter) was left in the hole for stability. HQ core was drilled from 140 m to a total depth of 497 m, with competent rock attained at a depth of 207 m. Following drilling, a downhole orientation survey was conducted to evaluate any deviation from vertical. Approximately 3 weeks after hole completion, a 5 KΩ thermistor string with 20 m thermistor spacing was installed with a data logger taking hourly readings. The string will remain in the hole until stable ground temperatures have been reached. Following drilling, YGS will be preparing for geological logs of RC samples and core, and compile the temperature profiles from thermistor data. The University of Alberta will provide rock property information on samples collected and feed the thermistor data into their larger study of the geothermal potential of Tintina Trench and the Rocky Mountain thrust system.

4. Results

4.1 Curie Point Depth Mapping

Witter and Miller's (2017) CDP map of Yukon, updated with improved results from Li et al. (2017) show that the CPD for south-central Yukon is relatively shallow and has a depth range of 12-27 km (Fig. 3). These CPD results agree well with an 18-23 km depth to Curie point estimated from a two-layer thermal model of the crust for southern Yukon (Witter et al., 2018). Geologically, the regions with shallower CPD values correspond to the accreted allochthonous terranes of the northern Cordillera (Fig. 1), while deeper CPD areas in the north and southeast portions of Yukon appear to be co-located with continental margin rocks of ancestral North America that exhibit lower heat flow. It is important to note that crustal heat estimates derived from CPD values do not include the positive thermal effects of shallow, radiogenic plutons that lie above the Curie point depth, nor the insulative effect of a thick package of overlying sedimentary rock. Such geologic features would serve to elevate the thermal potential of the crust above values estimated from CPD calculations. Overall, based upon the CPD results only, 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.

4.2 Radiogenic Heat Study

Cretaceous and younger plutons are widespread in southern Yukon (Fig. 4). The average granitoid has a characteristic radiogenic heat production value in the range of 2.5-2.7 μW/m3 (Rybach, 1981; Hasterok and Webb, 2017; Artemieva et al., 2017). Calculations of heat production from radioactive elemental concentrations in southern Yukon yielded several high heat production values, with most samples ranging from 3-10 μW/m3, and ~ 25 samples with values greater than 10 μW/m3 (Friend and Colpron, 2017). The higher heat production values are associated with Cretaceous plutons, particularly in the Thirtymile and Englishman ranges and the Cassiar Mountains, between the Teslin and Tintina faults (Fig. 4; max. values of 13.9, 12.2, 16.1 and μW/m3, respectively). Most notable are the samples associated with the Late Cretaceous Allan pluton in the eastern Cassiar Mountains northwest of Watson Lake where five samples associated with a uranium showing yielded values >20 μW/m3 (max. value 289 μW/m3). Other considerably higher values occur north of Faro and Ross River, in the Anvil and South Fork ranges (max. value of 13.8), and in mid-Cretaceous plutons in the Hess Mountains near the Northwest Territories border and Macmillan Pass (max. values of 10.4 and 9.1 μW/m3, respectively). Younger, Cenozoic plutons are most abundant in southwestern Yukon, in a northwest-trending belt extending from Carcross and Whitehorse, to north of Burwash Landing. These plutons yield slightly lower than average heat production values (average of 2.0 μW/m3), with some exceptions, notably local values >5.0 μW/m3 in the more differentiated plutons west of Whitehorse (Fig. 4).

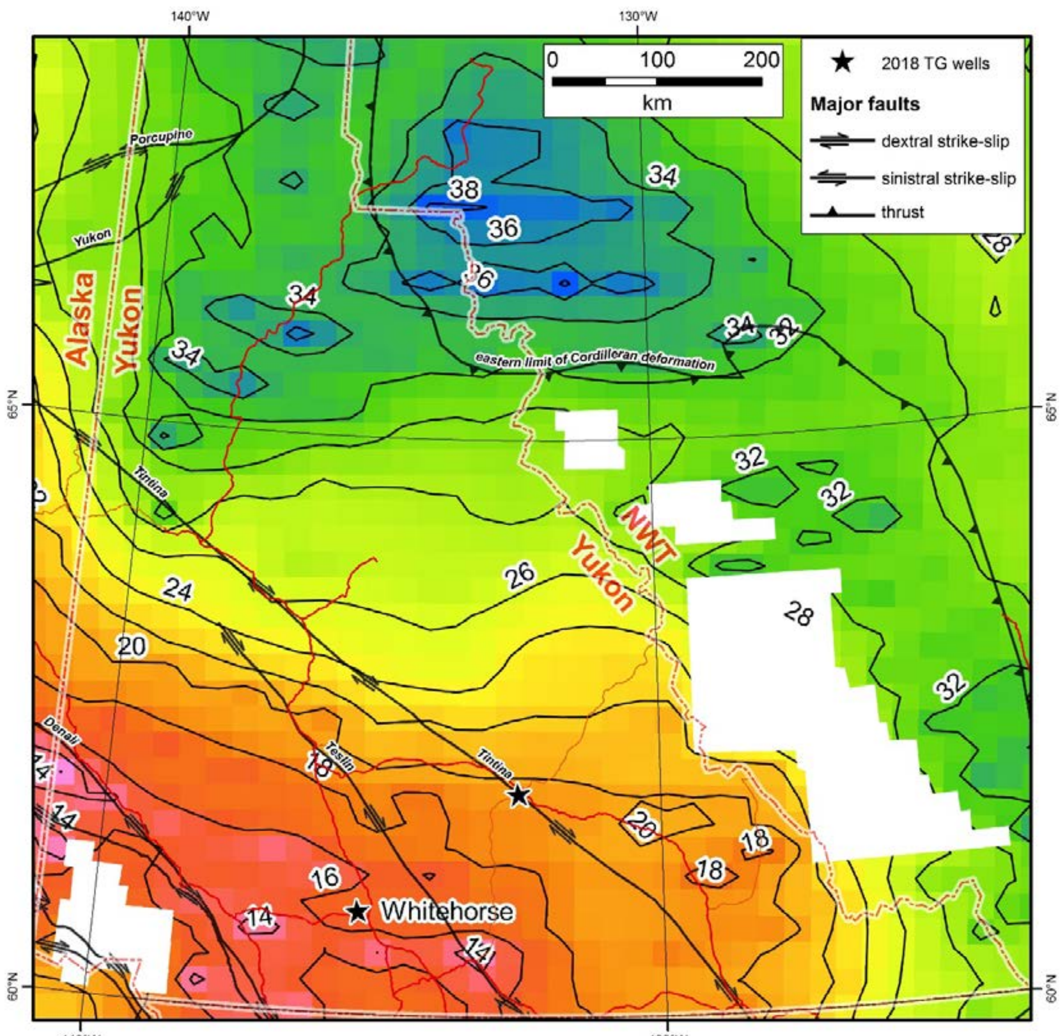

Figure 3. Curie Point depth (CPD) map for Yukon (generated from data of Li et al., 2017 by Witter et al., 2018). Depth contours in kilometres. The locations of the two TG wells discussed in this study are indicated by black stars. White polygons denote areas with no data.

4.3 Depth-Temperature Profiles from Historical Data Compilation

There are 23 sites in Yukon with 108 depth/temperature profiles (Fig. 1). Some locations have measurements from a number of wells in close proximity and some wells have several measurements. For sites with multiple measurements, results are typically consistent showing that the thermal field is stable at these sites. The depths of temperature records range from 9 to 792.5 m. A common characteristic of thermal gradients in wells of northern Canada is that they show a thermal inversion (Fig. 5a). Here the portion of the well log closest to ground surface shows an initial trend of decreasing temperature with depth, which at a certain depth then inverses to a normal trend of increasing temperature with depth. This phenomenon has been well studied and is considered a signal of climate warming, whereby a heat pulse is propagating downward and disruption of the near surface temperature field (Majorowicz et al., 2005). While this feature provides intriguing record of climate warming it also causes difficulty in assessing local geothermal gradient as the near surface record is spurious and not reflective of deeper thermal gradients.

Our assessment of well records in Yukon illustrate that the depth to the temperature inversion (only below which good thermal gradient records can be obtained) ranged from 10 to 100 m (Fig. 5b). For two sites the wells did not extend deep enough to obtain thermal records unaffected by the temperature inversion. This allows calculation of shallow thermal gradients from 21 sites (based on using data only below the temperature inversion). Results of shallow thermal gradients ranged from 3.9 to 70.1°C (Fig. 5c). However, the highest 2 gradients and the second lowest one are based on limited data records (< 50 m) and as such are suspect. Resulting data though do still show some higher geothermal gradients in Yukon, with the record at Faro having the highest reliable thermal gradient in the territory (40.4°C/km). The Carmacks gradient is intriguingly high but would require new data acquisition to verify.

4.4 Temperature gradient well at Takhini Hot Springs

The Takhini well encountered mostly sandstone, shale and tuffaceous strata of Whitehorse trough. Approximately two months after installation of the thermistor string, temperatures between 100 and 500 m were stable (≤ 0.1°C), while temperatures in the 20 – 100 m range were stable within three months. After six months, the upper 10 m still exhibited temperature fluctuations which can be attributed to changes in surface air temperature, and it would be expected that this shallow temperature would continue to fluctuate year-round. There is no permafrost at this location, as temperatures in the near subsurface are not consistently below 0°C.

The temperature gradient shows a subtle inversion to a depth of ~50 m (Fig. 6). Using data below the inversion, ground temperatures increase from 7.0 to 12.8°C to a depth of 450 m, which results in a geothermal gradient of 16.5°C/km, less than the average upper crust of ~25°C/km, and less than the average crustal temperature gradient predicted by the CDP data of Li et al. (2017) of ~39°C/km for the Takhini/Whitehorse area. Between 400 and 450 m, the temperature gradient appears to be nearly vertical. Vertical gradients may indicate a permeable aquifer, as temperature stabilization within the permeable zone can be attained through heat convection within fluids. In impermeable zones we would expect to see an increase in heat as heat is transferred by conduction.

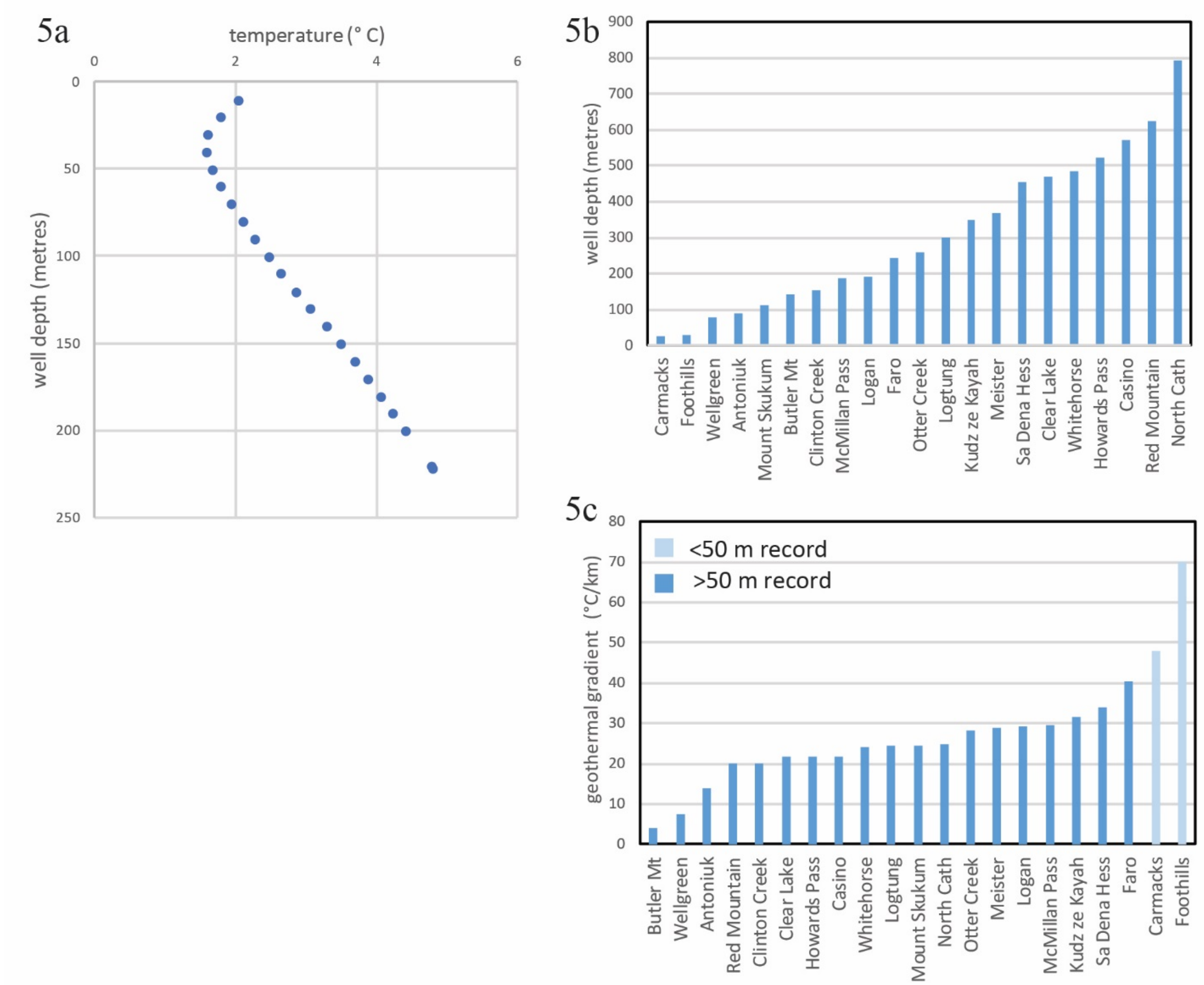

Figure 5. A) Depth temperature measurements for the Clear Lake area showing typical thermal inversion found in records of northern Canada. Geothermal gradients can only be estimated from wells with sufficient record below the inversion point. B) Depth to temperature inversion where possible to determine. C) Calculated geothermal gradients, for data below the temperature inversion, for well records in the Yukon. Light coloured bars indicate wells where temperature records below the inversion point are <50 m and are suspect.

Most notable about the temperature profile is the gradient of 250°C/km between 450-500 m, representing an increase in temperature from 12.8 to 25.3°C. It is unlikely that this gradient will continue much below this depth, as these values are most commonly seen in tectonically active areas such as volcanic rift zones (Iceland; e.g. Hjartarson, 2015) or volcanic hot spots (Hawaii; e.g. Fowler et al., 1980). More likely is that the spike could represent a temperature increase across a fault plane, separating two separate circulation systems with different thermal gradients. In this case, what happens to the gradient below the fault is speculative: it could settle back to the gradient above 450 m, i.e. 16.5°C/ km, which would put ground temperatures at ~34°C at a depth of 1000 m (Fig. 6), or it could return to the predicted values for the region, i.e. ~39°C/km, where the temperature at 1000 m would be 45 °C; or any number of options not presented here. Or, the temperature spike could also represent an isolated interruption in the temperature profile caused by warm fluid flow at this depth, for example along a permeable horizon or fault plane, below which the temperature reverts back to the shallower temperature profile with the same geothermal gradient (Fig. 6). In this case, ground temperatures at a depth of 1000 m would be in the range of 23°C. Alternatively, the distinct increase in temperature could reflect an impermeable zone of conductive heat transfer from a deeper aquifer. To confirm any of these hypotheses, deeper drilling would be required.

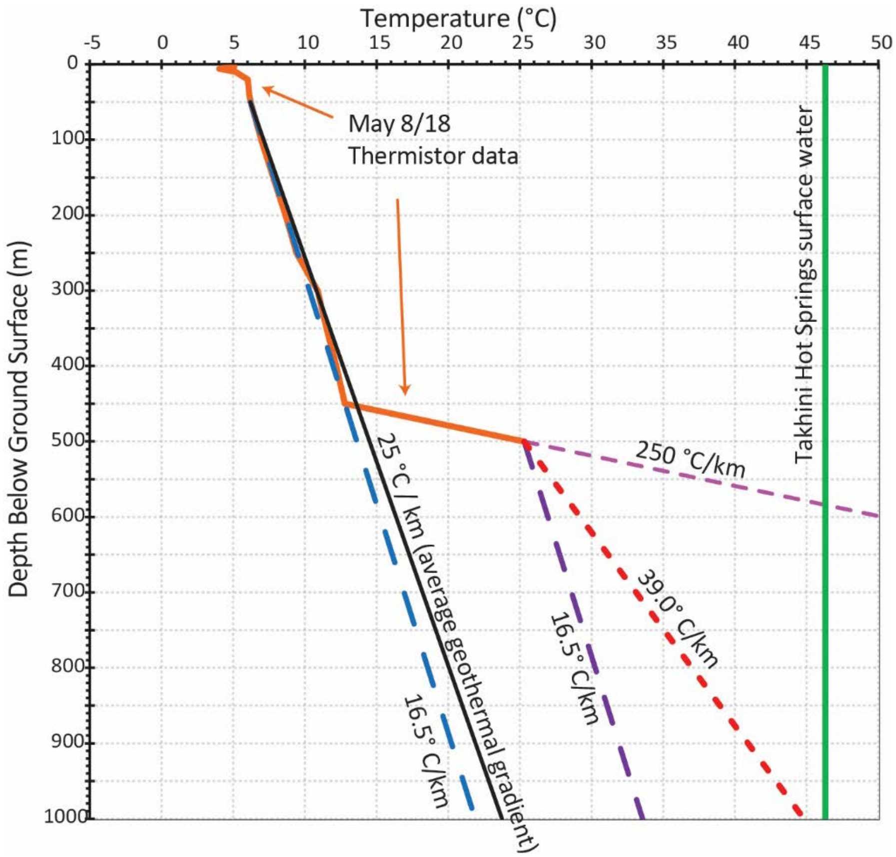

Figure 6: Stabilized downhole temperature data for the Takhini well, including interpretive geothermal gradients discussed in the text, average geothermal gradient, and the surface water temperature at Takhini Hot Springs.

4.5 Temperature gradient well in Tintina Trench

Cenozoic unconsolidated sediments were encountered in the Tintina well to a depth of 207 m. Precursory inspection of core suggests glacial sediments overlying older glaciofluvial and fluvial sediments. Competent sedimentary rock was encountered between 207-497 m, including siltstone, sandstone, and pebble conglomerate, however, its age and lithologic unit are currently under review. Substantial faulting was observed in the core, the presence of which made drilling and core recovery challenging.

Thermistor readings from 258 m and below were stable (variation was ≤ 0.1°C) immediately upon thermistor installation (i.e. 3 weeks after drilling ceased). The top 38 m were stable within a few days. These values record temperatures ≤0°C which gives a record of permafrost to at least a depth of 38.4 m (Fig. 7). Intervening thermistor beads were stable 5 weeks post-drilling. The 0 m reading is at ground surface and fluctuates with ambient air temperature. A thermal inversion can be observed to a depth of ~38 m. Below this depth, the temperature gradient is linear at 30.6°C/km (Fig. 7) which is higher than the average crustal gradient and aligns with the predicted average crustal temperature gradient from Li et al. (2017) CPD data. The linearity of the data suggests that the subsurface is comprised of relatively homogenous, low permeability rock that facilitates conductive heat transfer. There is no evidence of permeable zones in the temperature data (i.e. vertical gradient intervals) or temperature spikes that might suggest intervals of hot fluids.

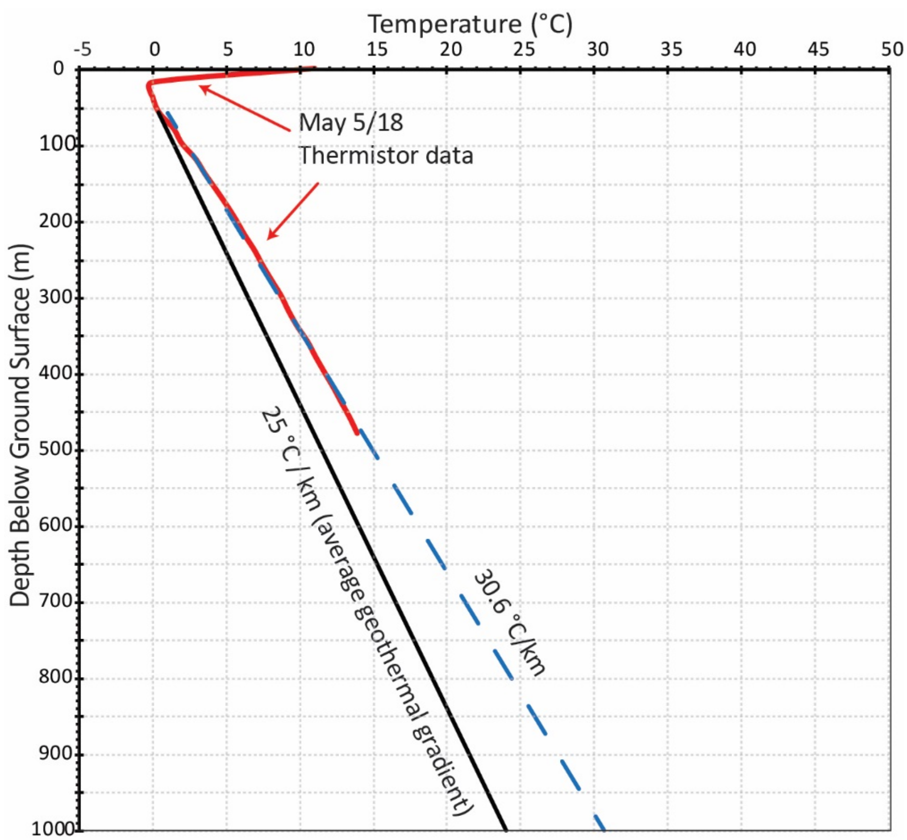

Figure 7: Stabilized downhole temperature data for the Tintina well, including the interpreted geothermal gradient.

5. Discussion

5.1 Utility of pre-existing data to explore for geothermal potential in Yukon

Although not specifically collected for geothermal research purposes, considerable pre-existing information was compiled for this study that helped to form a regional understanding of heat flow in the territory and facilitated delineation of areas most prospective for advanced exploration. The CPD results provide territorial coverage and indicate regions where one would expect higher vs. lower average geothermal gradients in the mid-crust. The shallower CPD depths (and inferred highest geothermal gradients) are in southern Yukon, with the shallowest in the southwest along the Denali fault, and deepening towards the east and north (Fig. 3). It is important to note that while the two CPD maps by Witter and Miller (2017) and Li et al. (2017) differed in terms of their CPD calculated values, the trends were consistent and thus should be used as a general prospecting tool rather than a precise identification of Curie point depths. Further, the CPD values do not reflect heat generation from shallower radioactive intrusive bodies, so its use along with other heat generation/flow data is necessary.

Likewise, the potential radiogenic heat production from granitoids indicates highest heat production in southern Yukon; but Cretaceous and younger granitoid plutons also only occur south of 64.5ºN, and most extensively in a belt below 62.5°N between the Denali and Tintina faults (Fig. 4). It is notable that Cretaceous plutons yielded higher heat production values than younger Cenozoic plutons (Friend and Colpron, 2017).

Although sparse, existing wellbore data indicates the highest reliable geothermal gradient is in Faro, along the Tintina fault, with values greater than the average crustal gradient of 25°C/km on or adjacent to the Tintina fault and eastward, which corroborates the location of highest heat flow values in Yukon indicated by Lewis et al. (2013). However, southwest Yukon is also intriguing. Although the shallow (<50 m) temperature records for Foothills wells suggest the calculated geothermal gradient of 70 °C/km is suspect, a deeper test well on the Denali fault in Burwash Landing does indicate an elevated gradient of 44°C/km in that area, and perhaps these data are less suspect than originally thought. Importantly, this study indicates that borehole data needs to be corrected for thermal inversions at depths up to ~100 m, location dependent, or spurious geothermal gradients will be generated. This requires adequate temperature collection in the upper 100 m of the borehole.

When used in conjunction, the pre-existing data indicates that geothermal potential in Yukon is highest in the south, particularly in the vicinity of Cretaceous plutons and/or associated with crustal-scale faults (e.g. Tintina). In the southwest, the Denali fault zone requires further studies, particularly as it is a zone of high seismicity, which may indicate fractured zones and increased permeability, a requirement in addition to a heat source that is necessary for a geothermal resource to be viable. Additionally, high values of radiogenic heat production (~6.0 $\mu W/m^3$), combined with 46°C water at surface make the Takhini Hot Springs area near Whitehorse another favorable target for further study.

5.2 TG well assessment

The two TG wells drilled for this study represent the first 500 m wells in Yukon that were rigorously investigated for temperature specifically for the purpose of geothermal exploration. The Takhini well does not indicate the presence of permafrost in the near subsurface, but has a thermal inversion to a depth of ~50 m, below which values are believed to represent true geothermal gradient. The data indicate warm water at a depth of 500 m below the surface, however, the well is not deep enough to effectively interpret this reading, and it is unknown whether this is related to the hot water observed at Takhini Hot Springs. It is also difficult to say whether the temperature gradient is higher than average. Further drilling at this location will be necessary to resolve these issues.

Below a thermal inversion of up to ~ 38 m, with permafrost to at least this same depth, the Tintina well shows a consistent, higher than average geothermal gradient of 30.6°C, however, not high enough at this location for power generation at an economic depth. The location along an antithetic fault to the Tintina does not appear to provide a high permeability vertical pathway delivering hot crustal fluids to the near surface, nor were intrusive rocks intercepted in the borehole, which were hypothesized at depth from the previous geophysical study by Mira Geoscience (2017). A higher than average geothermal gradient is interpreted from an exploration hole near Faro, also along the Tintina fault.

Figure 8: Photograph of truck sourcing water for Tintina well, ~6 km from the drill site. The lake lies in Tintina trench and the Pelly Mountains are observed in the distance.

Aside from the inconclusive results about either the geothermal potential of Tintina fault and the Takhini Hot Springs region, the study highlights some of the difficulties involved in designing and undertaking drill programs in frontier areas. It was the original intention to drill several wells at each location, but costs and time constraints ended up being the limiting factors in the study. The grant from SINED expired at the end of March 2018, having been granted in early 2016. Undertaking a project of this magnitude in two years was challenging. Drilling costs were substantially higher than anticipated as results of numerous delays. Cold weather challenged all parts of the field program, particularly for the Tintina well, where -40°C temperatures slowed the drill operations substantially. For example, water for diamond drilling was sourced from a local lake that repeatedly froze over (Fig. 8).

6. Conclusions

With primary funding from the Canadian Northern Economic Development Agency and Yukon Government, this collaborative project utilized historical temperature, geological, geochemical and geophysical data to gain an understanding of geothermal gradients and regional heat flow in Yukon. We also created a new dataset of subsurface geology and temperature measurements in two areas of suspected high geothermal energy potential: Takhini Hot Springs and Tintina Trench. Key findings from Curie Point mapping indicate that southern Yukon is the most likely place in the territory for higher than average geothermal gradients, particularly in south-central and southwest, near the Denali fault. Radiogenic heat production from Cretaceous plutons produces more heat than Cenozoic ones, with values up to 16 $\mu W/m^3$ in south-central Yukon between the Teslin and Tintina faults. Temperature profiles from historical exploration wells indicate higher than average temperature gradients on or near Tintina fault and eastward, with the highest gradient of 40°C/km near Faro.

New TG well data is inconclusive from the Takhini Hot Springs area, where a spike in temperatures to 25.6°C at 500 m depth may indicate the beginning of a steeper geothermal gradient at a fault plane, and/or warmer fluid flow within a permeable horizon, or any number of interpretations not discussed here. Further drilling is required to resolve this question, and whether this is hydrodynamically-related to the 46.3°C water observed ~2 km distance at Takhini Hot Springs. The Tintina well indicates a higher than average geothermal gradient of 30°C/km, however, the location does not indicate the presence of hot fluid flow from depth, nor a source of heat for power production at an economic depth from surface. Despite these findings, the project has significantly advanced our understanding of baseline heat production and geothermal gradients in Yukon, and we suggest further exploration in the following areas:

1) Extension of the TG well at Takhini Hot Springs by 100 meters or more to evaluate the temperature anomaly at the 500 m depth;

2) Step-out drilling in the 2 km between the Takhini well and the hot springs to evaluate subsurface geology and permeability to create a viable cross-section;

3) Drilling a TG well(s) near the Faro anomalous geothermal gradient of 40°C/km;

4) Identification of TG drill sites along the Denali fault.

In addition, we have a much better understanding of how to undertake a project of this magnitude in the North with time, economic, and partnership constraints to consider.

Continued short-term work on this project includes: logging the drill core from the Tintina and Takhini wells, and assessment of rock properties, e.g. thermal conductivity; further compilation of heat-generating potential of radiogenic granitoids; and incorporation and interpretation of the

Tintina well results into the larger geothermal study focused on the Tintina-Northern Rocky Mountain Trench. Most importantly, this information will be communicated to the residents of Yukon and their governing bodies to help educate them on the viability of geothermal energy in the territory and what is required to enhance the understanding of its potential as a clean energy source.

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