Evaluating geothermal potential in Yukon through temperature gradient drilling

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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 methods and results of the drilling of two ~500 m geothermal temperature gradient wells. The first was drilled in the fall of 2017 in the Whitehorse area, near Takhini Hot Springs, where a surface water seep measures 46°C. The second well was drilled in winter 2018 in the Tintina fault system, near Ross River. Results to date suggest warm fluids and possible permeable rocks in the Takhini well between 450 and 500 m from surface, and a higher than average geothermal gradient of ~31°C/km in the Tintina Trench near Ross River. The results do not indicate temperatures for power generation at economic depths, however, they are encouraging enough to warrant further geothermal studies in southern Yukon.

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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 (Fig. 1), abundant plutonic rocks, extensive sedimentary rock cover, and numerous seeps and hot springs (Fig. 1) 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 (TKC), and Ross River Dena Council (RRDC). This paper describes one element of the study, specifically the selection of drill locations and results from two TG wells in southern Yukon near the communities of Whitehorse and Ross River. The study aligns with Canada's interest in reducing remote northern communities' 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.

Background

Energy Supply

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 use for district heating applications (Raymond *et al.*, 2015). In Yukon ~94% of the territory's power is currently produced by hydro-generating stations and distributed to most communities (Yukon Energy Corp., 2018), making Yukon one of Canada's leaders in "green" energy. However, Yukon's population is growing rapidly and there are several advanced mineral exploration programs, with a few likely to develop into mines, which will put pressure on the existing electrical grid, or require on-site electrical generation in areas not connected by transmission lines. 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. As no operating pipeline connects Yukon to southern Canada, diesel must be trucked up to the territory along the Alaska Highway and distributed to communities on the local road network. Old Crow, as a fly-in community that uses diesel for electrical production, requires all petroleum products to be flown in at a large expense. Direct usage of geothermal energy in Yukon is limited to low-grade systems to keep water systems from freezing (*e.g.*, Mayo and Haines Junction), and the Takhini Hot Springs resort north of Whitehorse which uses the water for bathing. It is estimated that 74% of space heating in 2016 used fossils fuels (oil and propane), supplemented by 26% renewable sources (wood and wood pellets, and electricity; Yukon Government Energy Branch, 2018). 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.

Previous Geothermal Research in Yukon

In addition to traditional knowledge of hot spring or seep locations from Yukon First Nations (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,b; 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, 2005; Majorowicz

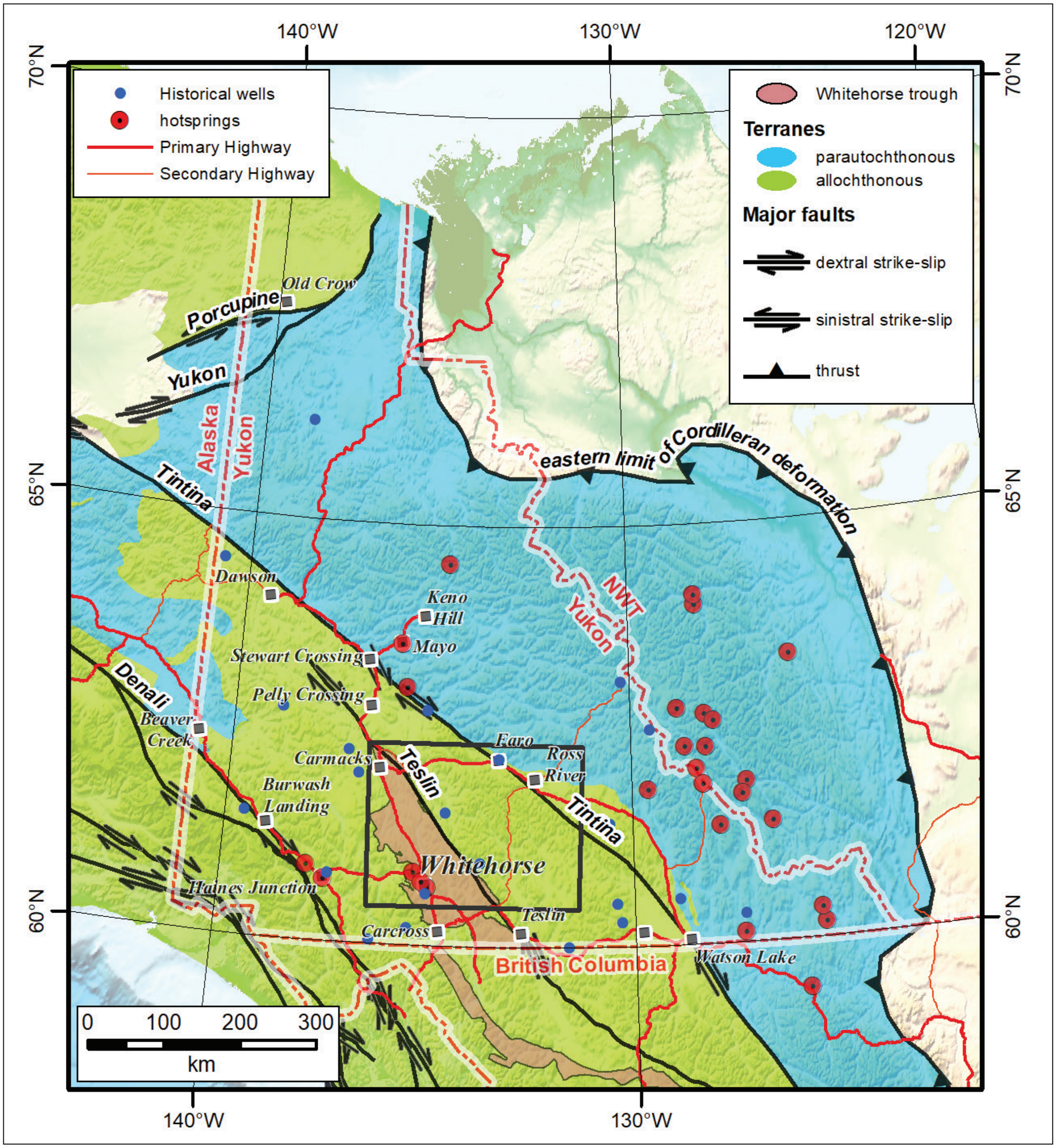

Figure 1. *Simplified terrane map of Yukon showing the distribution of parautochthonous rocks of the Ancestral North American margin, allochthonous terranes of island arc and oceanic affinities, and major crustal faults. The Jurassic Whitehorse trough is shown in brown. Also indicated are the locations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

and Dietrich, 1989; Fig. 1). However, these data are sparsely distributed, mostly distal to population centres, are at variable depths, and typically only have one temperature data point (basal temperature only), which can give misleading geothermal gradients. 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. 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 and 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 on behalf of the Kluane First Nation. The well was drilled in the community of Burwash Landing (Fig. 1) to determine the potential of future geoexchange applications. Although the report was never published, the results indicated an elevated geothermal gradient, with the well yielding 16°C water.

In 2014, the Dena Nezziddi Development Corporation of RRDC commissioned a geothermal exploration program of the Tintina fault zone near Ross River (Figs. 1 and 2) 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 favourability 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).

Geological Setting

On a regional scale, the rocks in Yukon can be divided into two main domains: rocks that developed on the continental margin of ancestral North American (Laurentia) mainly during the Paleozoic, and those that accreted to the western margin of North America, mainly during the Mesozoic. For the most part, the dividing line between Laurentian or parautochthonous rocks to the northeast and accreted or allochthonous terranes to the southwest is the northwest-striking Tintina fault: one of the most prominent physiographic and geologic features in Yukon (Figs. 1 and 2). The fault is a steeply northeast-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 location of one of the TG wells described in this study, the fault zone is approximately 4 to 10 km wide and consists of six prominent subparallel fault strands linked by a series of high-angle extensional faults (Fig. 3; 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 sedimentary rocks, in many areas covered by Pleistocene glaciofluvial and moraine deposits (Mira Geoscience, 2017; Turner, 2014).

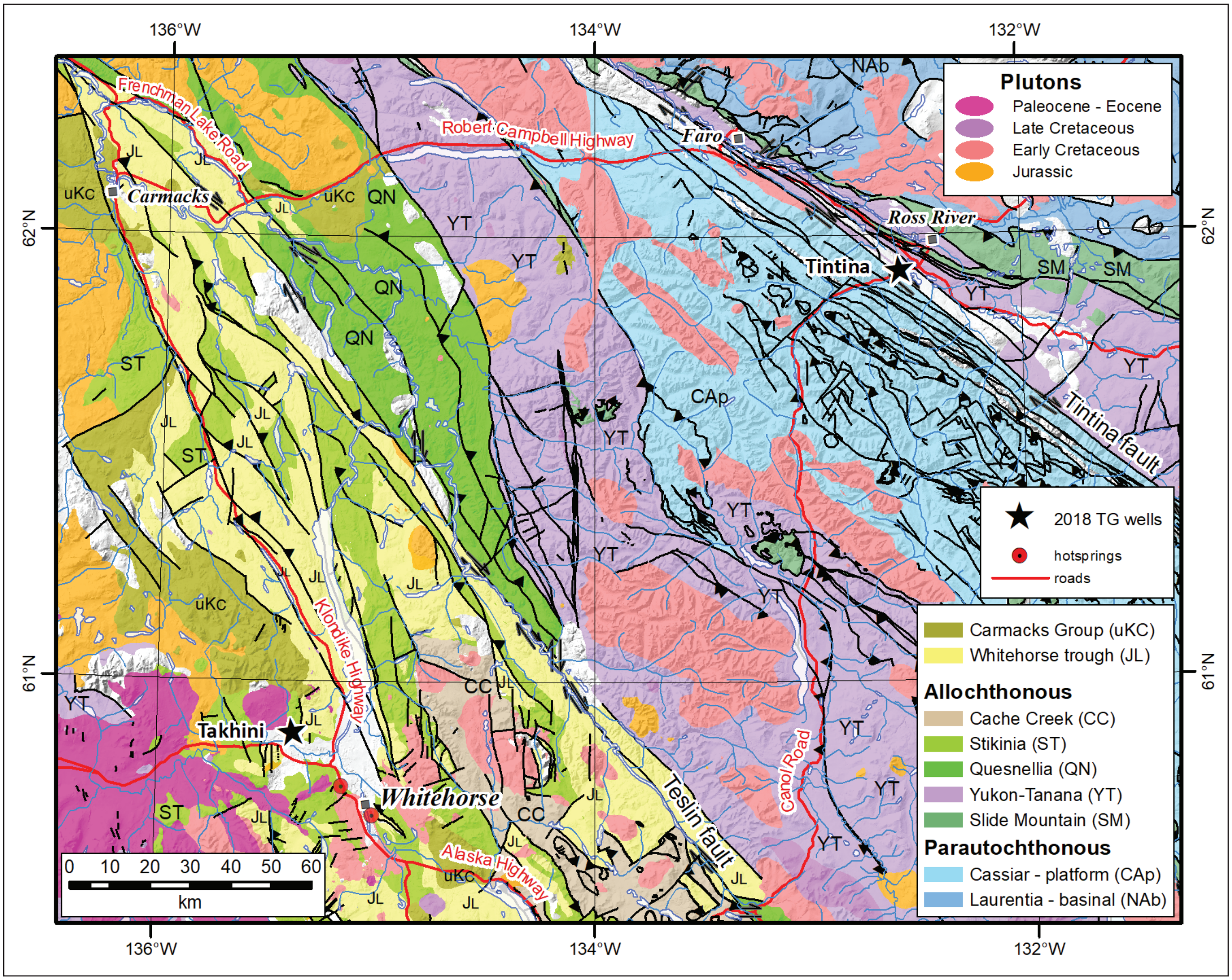

Figure 2. *Simplified geological map of part of southern Yukon showing locations of the two TG wells drilled as part of this study. Geology from Yukon Geological Survey (2018).*

Southwest of the Tintina fault, the Whitehorse trough is a Mesozoic marine sedimentary basin that occupies an elongated belt stretching from north of Carmacks, and extending 650 km south through Whitehorse and into northern British Columbia (Figs. 1 and 2). The basin comprises Lower to Middle Jurassic sedimentary and volcanic rocks that were deposited in a synorogenic basin developed during accretion of allochthonous island arc and oceanic terranes (Colpron et *al*., 2015). Near Whitehorse, and the Takhini TG well location in this study, Jurassic sedimentary rocks of Whitehorse trough overlie Upper Triassic marine sedimentary, volcanic and volcaniclastic rocks of island arc affinity (Hart, 1997; Fig. 4). Approximately 2 km west of the drill location, an Eocene (54 Ma; Hart, 1997) granitoid pluton intrudes Whitehorse trough and older rocks, including Upper Triassic thick-bedded limestone (Figs. 2 and 4; Yukon Geological Survey, 2018).

Regional ground temperature data for Yukon is sparse. Geothermal gradients compiled for Canada are shown in Figure 5, sourced mainly from bottom-hole temperatures in exploration wells (Grasby et *al*., 2012; see Fig. 1 for Yukon well locations). This sparse data set indicates that southern Yukon has a geothermal gradient

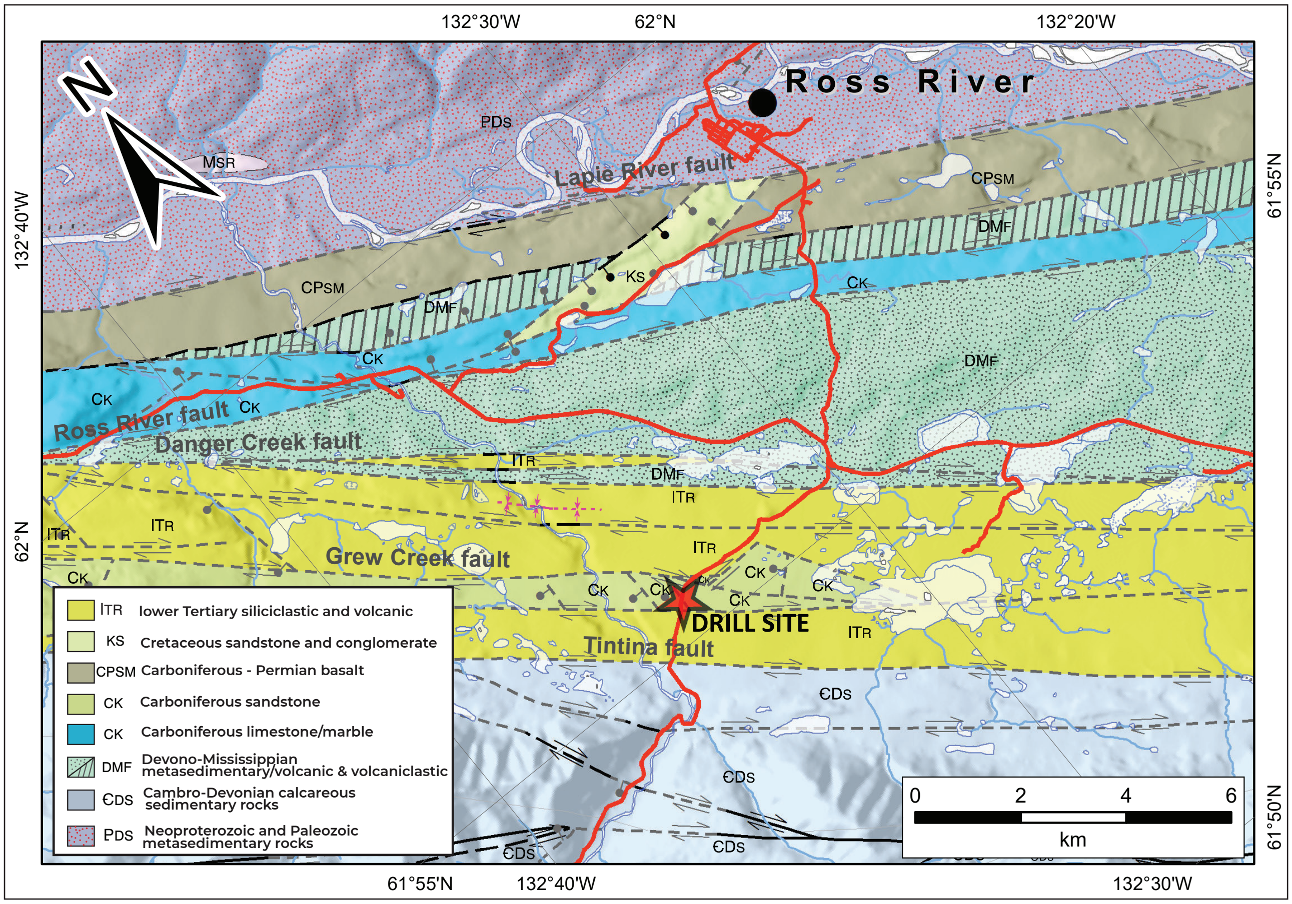

Figure 3. *Geology in vicinity of Tintina Trench TG well southwest of Ross River (geology after Mira Geoscience, 2017).*

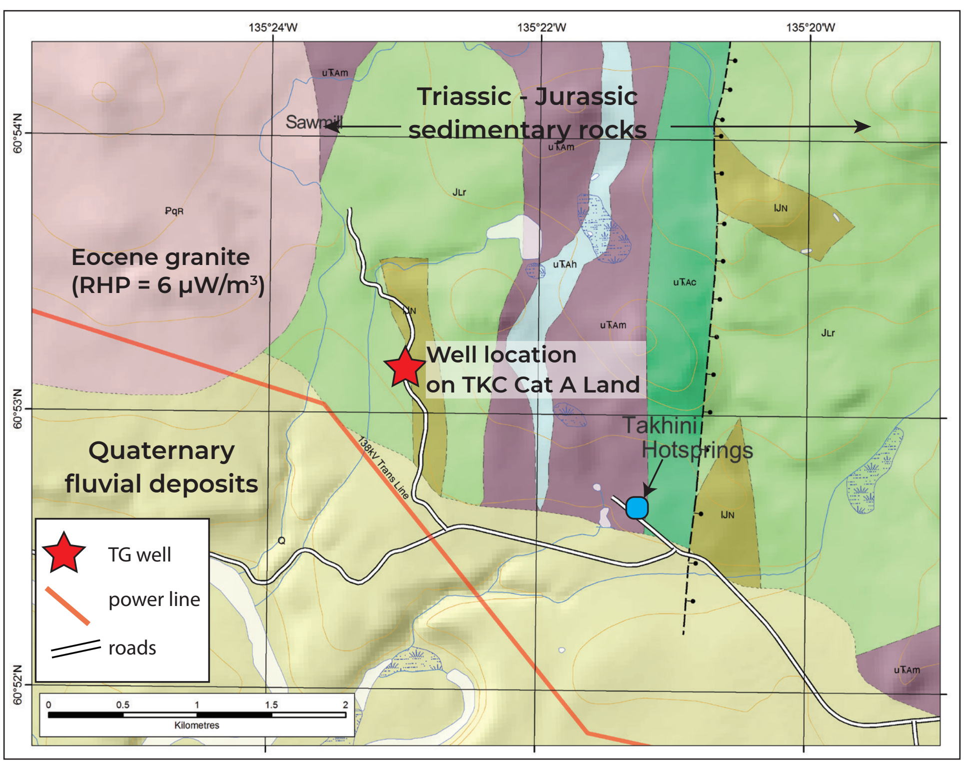

Figure 4. *Geology in vicinity of Takhini TG well (geology from Yukon Geological Survey, 2018). RHP stands for radiogenic heat potential; TKC Cat A Land stands for Ta'an Kwäch'än Council Category A Settlement Land.*

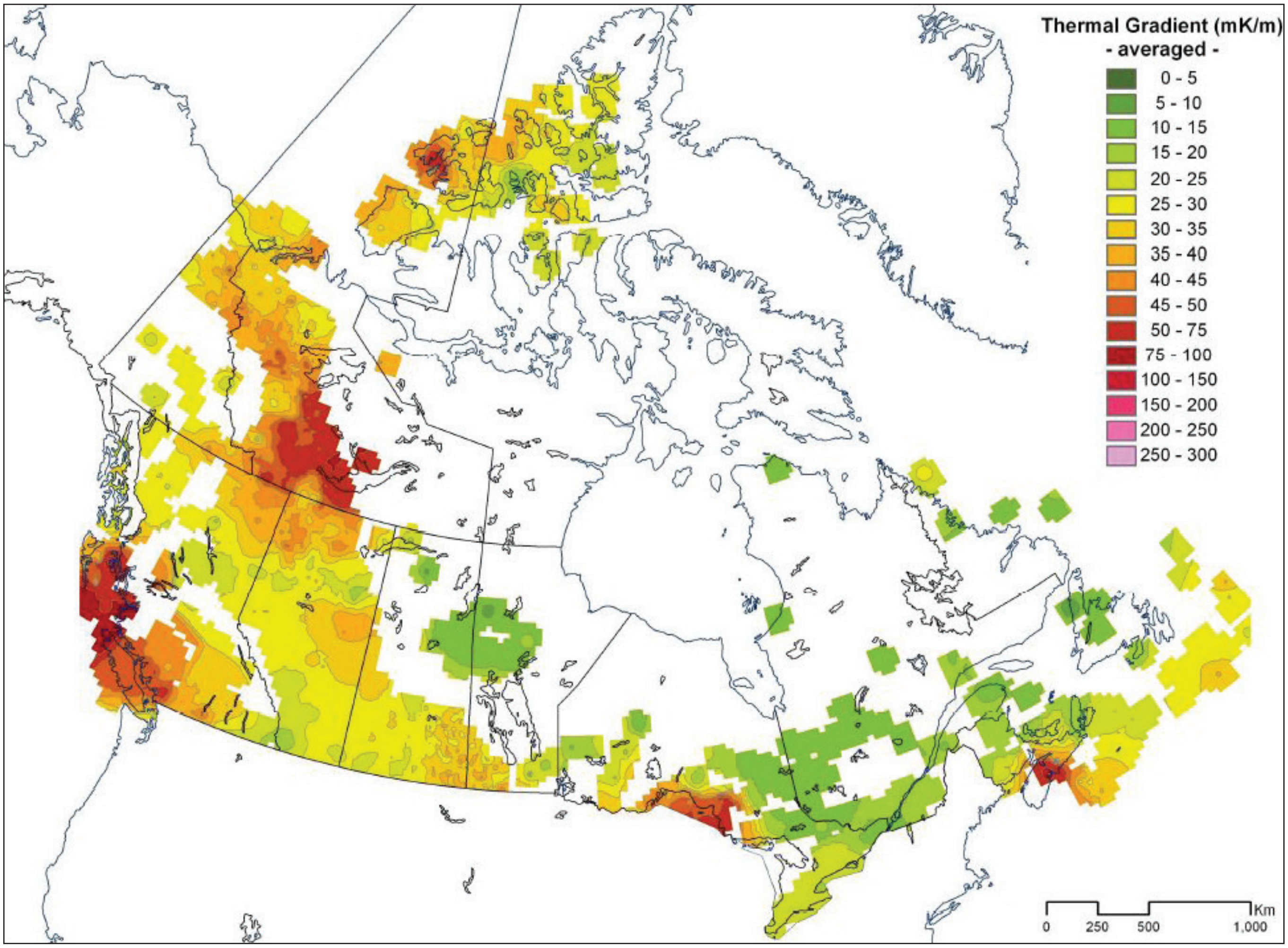

Figure 5. *Contour map of the geothermal gradient in Canada (Grasby et al., 2012). Note that mK/m units are equivalent to °C/km.*

of ~25°C/km which is equivalent to the global average for the upper crust, with slightly higher values of up to 40°C/km in the north. However, it is clear that there is a distinct lack of data overall, particularly in southern Yukon. Based on the regional geological setting, Yukon has geothermal potential for high temperature power generation from volcanic and hot sedimentary basin settings in the south, and potential for direct heat/exchange systems from either cool sedimentary basin settings or fractured rock throughout the territory (Fig. 6). A goal of this study is to fill in some of the gaps in the regional ground temperature data set.

Methods

Prior to drilling, YGS undertook a series of desktop studies to identify potential drill sites including geological evaluation, Curie Point Depth Mapping (CPD) and calculation the radiogenic heat potential of Cretaceous and younger granitoid rocks. Methods and results of the CPD can be found in Witter and Miller (2017) and Witter *et al.* (2018), and the distribution of radiogenic granitic rocks in Friend and Colpron (2017). The CPD mapping suggests that the greatest heat flow to surface in the territory is in south-central and southwestern Yukon, results that are corroborated by the global study of CPD by Li *et al.* (2017). The areas of highest radiogenic heat potential from granitic

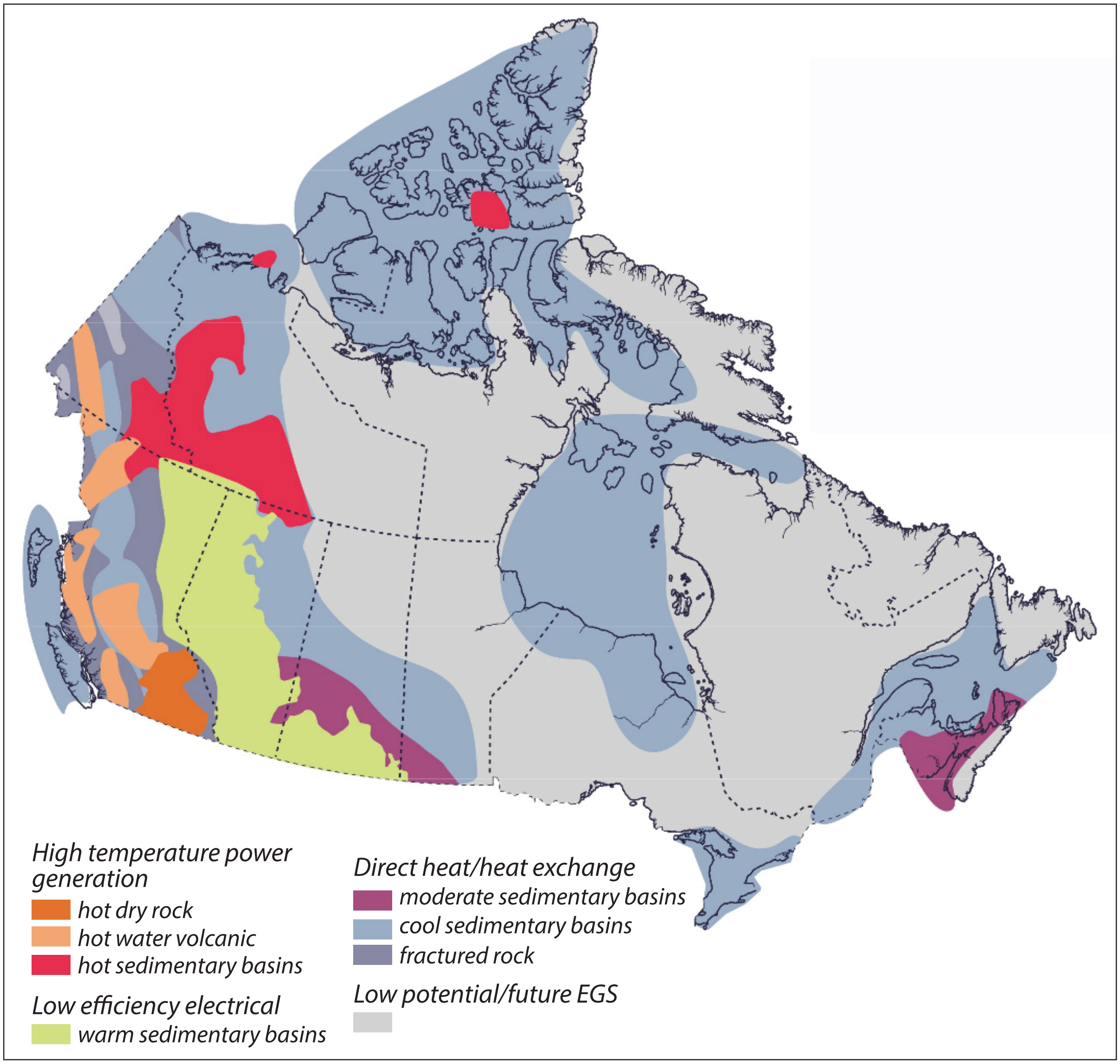

Figure 6. *Geothermal potential map of Canada based on end use (Grasby et al., 2012).*

rocks are associated with Cretaceous (not younger) granite, particularly northeast of Tintina fault and in a belt between the Teslin and Tintina faults. An additional exercise was conducted to identify potential drill targets based on non-geological factors such as road access, distance to power lines and population centres. Although several targets were identified as good candidates, adequate funds were available to drill two 500 m wells only. After considerable discussion, a decision was made to drill one hole close to Takhini Hot Springs, near Whitehorse, and the other hole near Ross River, in the Tintina Trench. These two locations allowed for the testing of two potential geothermal settings in southern Yukon.

The first site, near Takhini Hot Springs, approximately 30 km northwest of Whitehorse (Takhini on Fig. 2), was chosen to test a hypothesis that the hot water at the springs is the result of the radiogenic heating of meteoric water hosted in a permeable carbonate host rock. The drill location is about halfway between the hot springs and exposures of a radiogenic granitoid pluton (~6 μW/m³) ~2 km to the west (Fig. 4). Limestone is observed in the area as well. The well site is located on Settlement Lands of the TKC First Nation who granted permission to locate the well here. TKC's development corporation (Da Daghay Development Corporation) was hired to manage contracts for drilling, support services and thermistor installation. 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 during this period. The first 50 m was drilled using a reverse circulation (RC) drill with a 241 mm (9.5 inch) bit. Bedrock was encountered within one metre of the surface. This section of the hole was cased and cemented to ensure isolation of any potential aquifers. The bottom 450 m was drilled using a diamond drill coring rig with an HQ (63.5 mm or 2.5 inch) 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 nodes spaced at 50 m intervals for most of the well, and closer spacing (10 m intervals between 10 and 50 m depth; 3 m intervals from surface to 10 m) to document the thickness and temperature of permafrost, if present. The thermistor was connected to a multimeter at surface which required periodic manual readings. The thermistor was removed from the hole in the spring of 2018, and the site remediated.

The Tintina well target near Ross River was chosen to test a geothermal model of meteoric water circulation in a deep crustal fault zone. The location was identified from an analysis of 10 potential sites initially proposed in a technical study by Mira Geoscience (2017) for the Dena Nezziddi Development Corporation. The TG well location is in the right-of-way of the South Canol road (km 216; Figs. 1, 3 and 7), in an area of complex faulting, and near a buried igneous body inferred from geophysical models (Mira Geoscience, 2017). The drilling of this well was done in partnership 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 29 (34 days). Temperatures in nearby Faro averaged -14°C during the drilling period, but were as low as -40°C at the drill site, causing delays and equipment problems. The original intent was to drill with an RC rig to consolidated bedrock, which 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 metres of PW casing

Figure 7. *Photograph of Tintina Trench drill site looking west towards the Pelly Mountains.*

(140 mm/5.5 inch 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. Approximately 3 weeks after completing the hole, a 5 KΩ thermistor string with 20 m node spacing was installed, and a data logger was taking hourly readings. The string was removed from the hole in September 2018, after stabilized temperatures had been reached. Drill core from the hole is being logged by the YGS. The University of Alberta has sampled the core and will be conducting a variety of rock property studies (porosity, permeability, XRD mineralogy) as part of a larger study of the geothermal potential of Tintina Trench and the Rocky Mountain thrust system.

Results

Temperature Gradient Well at Takhini Hot Springs

The Takhini well encountered mostly sandstone, shale and tuffaceous strata of the Whitehorse trough. Approximately two months after installation of the thermistor string, temperatures at depths between 100 and 500 m were stable (with variations ≤0.1°C), while temperatures at depths 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 shallow depth temperatures 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 (decrease in temperature with depth) to a depth of ~50 m (Fig. 8). Temperature inversions are common in wells in the north, and are considered a signal of climate warming, whereby a heat pulse is propagating downward and disrupting the near surface temperature field (Majorowicz et *al.*, 2005). 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 CPD 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.

Most notable about the temperature profile is the marked temperature increase from 12.8 to 25.3°C at depths between 450 and 500 m. This temperature increase may represent a temperature increase across a fault plane, separating two separate circulation systems with different thermal gradients. It may also represent a fault plane or permeable rock interval hosting warm fluid. What happens to the gradient below the well 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. 8); or it could return to the predicted values for the region from the CPD study, *i.e.*, ~39°C/km, where the temperature at 1000 m would be 45°C; or any number of options not presented here. The temperature spike

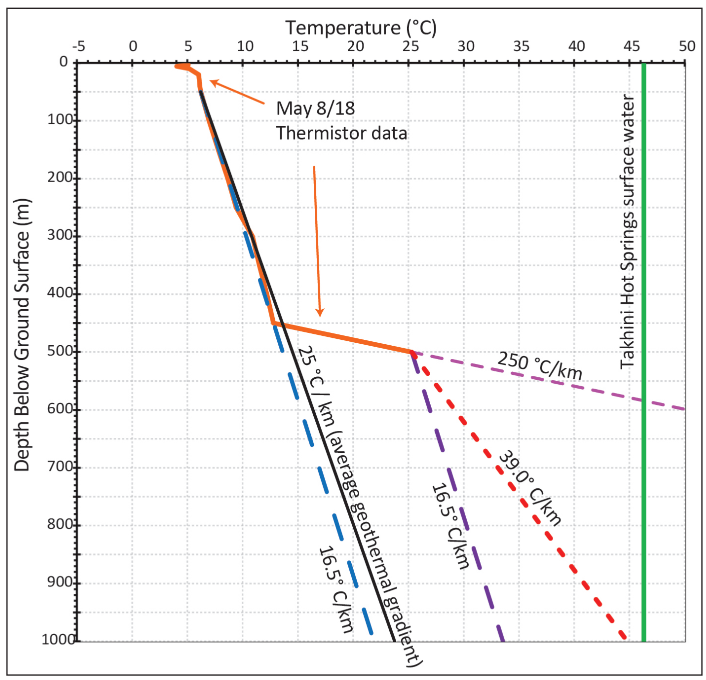

Figure 8. *Stabilized downhole temperature data for the Takhini well, including interpretive geothermal gradients discussed in the text, average geothermal gradient, and the surface water temperature at Takhini Hot Springs.*

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. 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. An unlikely scenario is that the gradient continues at the rate observed at the bottom of the hole, *i.e.*, 250°C/km, 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).

Temperature Gradient Well in Tintina Trench

Cenozoic unconsolidated sediments were encountered in the Tintina well to a depth of 207 m. Preliminary inspection of the core suggests glacial sediments overlying older glaciofluvial and fluvial sediments. Competent sedimentary rock was encountered between 207 and 497 m, including siltstone, sandstone, and pebble conglomerate, however, the age and stratigraphic affinity of these rocks are currently under review. Substantial faulting was encountered in the core, 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. 9). 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. 9) 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 comprises 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.

Discussion

The two TG wells drilled for this study represent the first drilled to a depth of 500 m 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 near 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/km, however, not high enough at

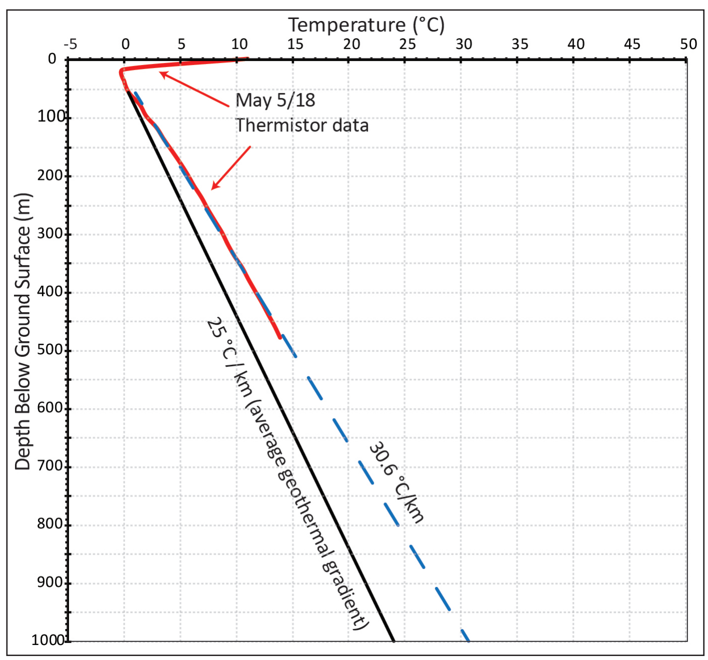

Figure 9. *Stabilized downhole temperature data for the Tintina well, including the interpreted geothermal gradient.*

this location for power generation at an economic depth. The location along an extension fault 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).

This study also highlights some of the challenges involved in designing and undertaking temperature gradient drill programs in frontier areas. For example, the presence of permafrost and thermal inversions caused by ambient air temperature and climate change require drilling to adequate depths to access true geothermal gradient readings. These phenomena are well known in the Canadian north, and their depth of propagation increases northward (*e.g.*, Fraser et *al*., 2018; Majorowicz et *al*., 2005). Further, it was the original intention to drill several wells at each location, but costs and time constraints ended up being limiting factors in this study. Drilling costs were substantially higher than anticipated as a result 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. 10).

Conclusion

This collaborative project created a new data set of subsurface geology and temperature measurements in two areas of suspected high geothermal energy potential: Takhini Hot Springs and Tintina Trench. New TG well data are inconclusive from the Takhini Hot Springs area, where a spike in temperatures to 25.6°C at 500 m depth may indicate the upper limit of a larger geothermal gradient across 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 at Takhini Hot Springs, ~2 km to the east. The Tintina well indicates a higher than average geothermal gradient of 30°C/km, however,

Figure 10. *Photograph of truck sourcing water for Tintina well, ~6 km from the drill site. The lake lies in the Tintina Trench and the Pelly Mountains are observed in the distance.*

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.

Continued short-term work on this project includes logging the drill core from the Tintina and Takhini wells, and assessment of rock properties and thermal conductivity being carried out at the University of Alberta; further compilation of heat-generating potential of radiogenic granitoid rocks; and incorporation and interpretation of the Tintina well results into the larger geothermal study focused on the Tintina-Northern Rocky Mountain Trench. Longer term initiatives include assessment of ground temperature along the Denali fault, where CPD results and previous drilling by EBA Engineering Consultants Ltd. show high heat flow potential, and identifying drill targets near heat producing radiogenic granites in southern Yukon.

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