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Yukon Geothermal Research Program 2016-2025

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INTRODUCTION

In 2016, the Yukon Geological Survey (YGS) initiated a research program to better understand the potential for geothermal resources in Yukon, a territory located in Arctic Canada. One of the motivations for the program was to provide a geoscience foundation for future work to explore and develop geothermal direct-use heating opportunities in the territory. Yukon has a cold climate with an average annual temperature at or below 0 °C. Water and space heating are provided primarily by hydroelectricity, natural gas, diesel, or wood (Government of Yukon, 2018). In addition, there are many off-grid communities in the territory that are 100% dependent on diesel for electricity generation and wood for heating. Expansion of hydroelectric resources in Yukon is difficult, and as a result, there is increasing demand for local sources of renewable energy for direct-use heating. Yukon is in the northern Canadian Cordillera and is made up of allochthonous terranes accreted to the western Laurentian continental margin and dissected by major, crustal-scale fault zones (Figure 1A). Southern Yukon was heavily glaciated and hosts numerous thermal springs but no active volcanism. At present, geothermal resources are exploited at one hot pool/spa resort in Yukon. In addition to YGS personnel, contributors to the 10-year geothermal program included the Geological Survey of Canada, geophysical data acquisition firms, drilling companies, independent geoscience consultants, and researchers from the following Canadian universities: University of Alberta, University of Calgary, University of Victoria, and the Institut national de la recherche scientifique (INRS).

1 METHODS

Some key datasets in the YGS geothermal research program included: a Curie point depth (CPD) map, radiogenic heat production data, temperature gradient hole data, new geophysical data (e.g., gravity, electromagnetic, and passive seismic), and new 3D geology models.

Curie point depth mapping is a method which utilizes regional-scale aeromagnetic survey data to map the depth in the Earth's crust to the Curie point temperature (~580 °C). Regions found to have shallow Curie point depths are expected to have higher heat flow and, therefore, a higher likelihood of geothermal energy resources that are accessible via drilling. The Yukon portion of the global Curie point depth map from Li et al. (2017) was used for this project (Figure 1B).

Heat generation from radioactive decay of U, Th, and K can be an important source of geothermal heat. Lithogeochemical data from >2000 plutonic rock samples from across Yukon were compiled. The compilation included both new rock samples and existing geochemical data in YGS archives. Heat generation was calculated using the method of Rybach (1981).

New subsurface temperature data were obtained from temperature gradient holes drilled by YGS as part of this project as well as by measuring downhole profiles in existing holes. Downhole temperatures were measured with purpose-built thermistor strings, Distributed Temperature Sensing (DTS), and a temperature and pressure downhole logger. Drilling programs undertaken by YGS near Ross River and Takhini Hot Springs included both reverse circulation and diamond drill core rigs with HQ-sized (63.5 mm or 2.5") core. The YGS drill program near Burwash Landing used a mud rotary drilling method with an 11 7/8 " (302 mm) hole and an 8" (203 mm) casing to the bottom of the well.

YGS directed the collection of geophysical data at five separate communities which included new measurements at 2090 gravity stations, 329 Extremely Low Frequency - Electromagnetic (ELF-EM) stations, 60 audiomagnetotelluric (AMT) stations, 89 magnetotelluric (MT) stations, and 167 passive seismic stations. Gravity and AMT/MT stations had nominal spacing of ~500 m and ~2 km, respectively. 3D inversion modelling of the geophysical data was used in combination with bedrock and surficial geology, water well data, and rock property data to generate 3D geological models at the five Yukon communities.

2 RESULTS

The research program began with compilation of geothermally relevant geoscience data already in YGS archives which included information on thermal springs, heat flow measurements, Neogene volcanism, bedrock geology and geologic structures, water wells, aquifer chemistry, and radiogenic heat production (Figure 1). These data were used to identify several potential geothermal systems near population centres in fault-controlled, hot sedimentary aquifer, and radiogenic granitoid geologic environments in Yukon. Note that a geothermal play-fairway analysis was not considered because much of Yukon is unpopulated and identification of potential geothermal systems in remote, roadless areas is not helpful. Preliminary analysis of the potential geothermal systems suggested that resource temperatures found in Yukon were likely 50 –100 °C for radiogenic geothermal systems but potentially >100 °C for hot sedimentary aquifer systems (Witter, 2016).

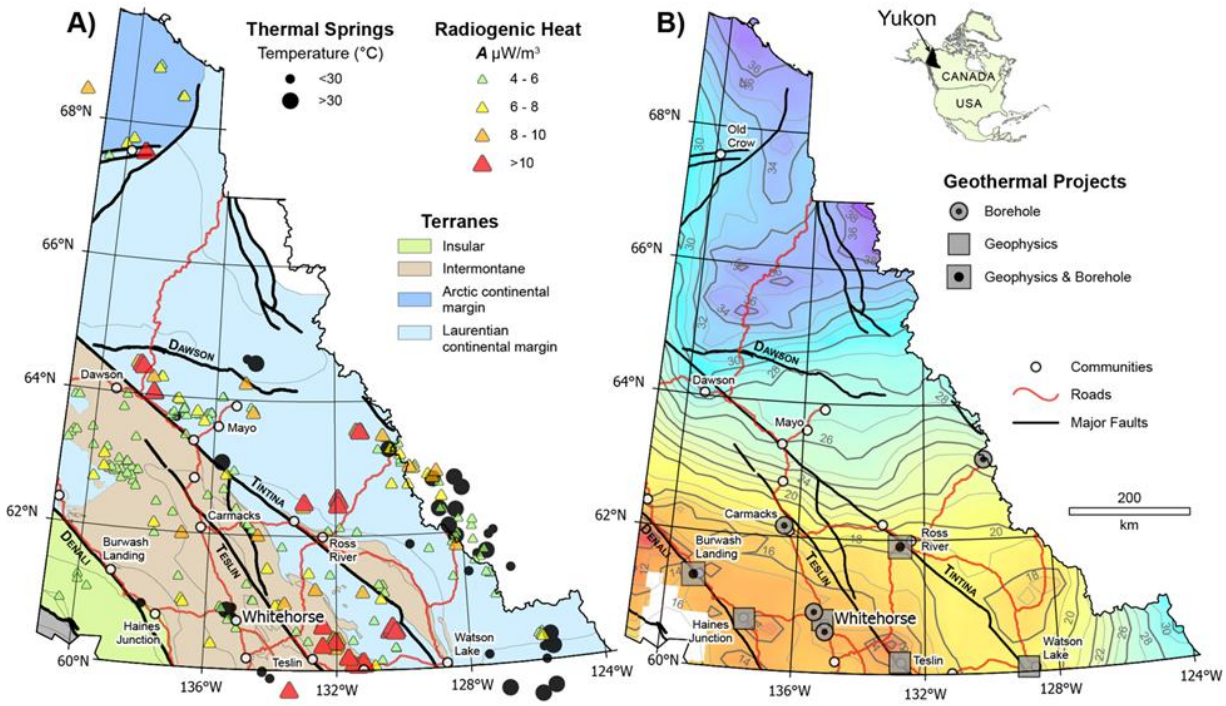


Figure 1. A) Simplified terrane map of Yukon showing major faults, the locations of thermal springs and radiogenic granitoid rocks with anomalous A value > 4 µW/m³. B) Curie point depth map of Yukon (after Li et al., 2017; contours in km) and locations of geothermal projects undertaken by the Yukon Geological Survey and research partners since 2016. Inset shows the location of Yukon in North America.

Yukon hosts 21 thermal springs divided into two categories: hot springs (> 30 °C; n=8) and warm springs (< 30 °C; n=13). Spring discharge rates vary from 1-45 L/s and reservoir temperatures based upon silica geothermometry have the range 15-164 °C (with 2/3 of the springs having <100 °C). Many of these thermal springs are located far from human habitation or in protected areas and, therefore, are not readily accessible for geothermal exploration and development.

Legacy temperature gradient data (Lewis et al., 2003) from mineral exploration boreholes suggested elevated crustal heat flow in southern Yukon (90-105 mW/m^2) compared to the global crustal average (~64 mW/m^2). However, the temperature gradient data were sparse and few so the resulting heat flow map for Yukon had large gaps. Thus, Curie point depth mapping (Li et al., 2017; Witter et al., 2018) was applied, which confirmed shallow CPD values (i.e., inferred high heat flow) across the southern half of the territory (Figure 1B). The southwest corner of Yukon showed the shallowest CPD values and coincides with the location of the Denali and Teslin faults.

Temperature gradient wells were drilled by YGS at three locations: 1) near Takhini Hot Springs (~30 km northwest of the capital Whitehorse); 2) within the Tintina fault zone near the town of Ross River in central Yukon; and 3) along Duke River within the Denali fault zone in southwest Yukon (Figure 1, Table 1). The Takhini well was sited near a known, Eocene radiogenic pluton (Fraser et al., 2018). The Ross River and Duke River wells were both sited in structural settings identified in previous geoscience studies (Mira Geoscience, 2017; Witter, 2020). The Ross River and Duke River wells showed linear, conductive temperature gradients below the level of permafrost (Fraser et al., 2018; Sternbergh and Colpron, 2025). In contrast, the Takhini well had an unusual profile consisting

of a linear temperature gradient of ~17 °C/km to a depth of 450 m, while the gradient increased dramatically to ~250 °C/km in the bottom 50 m of the well. The sudden increase in downhole temperature is interpreted as the transition from a cooler, conductive heat transfer regime to a higher temperature forced convective heat transfer regime (Langevin et al., 2020). The overall average gradient for the Takhini well is ~40 °C/km. The Takhini and Ross River wells have been plugged and abandoned. In contrast, the Duke River well was cased and instrumented for long-term temperature and microseismic monitoring and is ready for re-entry and deepening in a future drilling program.

Downhole temperatures in four other wells (drilled by other parties) were measured by YGS using a dual-channel downhole logger. Two wells drilled into granitoid rocks (Carmacks Copper WC-002 and North Star NS12-18) had low temperature gradients (23-25 °C/km; Table 1). A third well, Carmacks EY22-01, was drilled into the sedimentary rocks of the Whitehorse trough and had a higher temperature gradient (30 °C/km; Table 1). The KFN-L well in Burwash Landing (southwest Yukon) had been drilled into Quaternary sediments and has an even higher temperature gradient (49 °C/km; Table 1). Overall, the average temperature gradient values obtained from sedimentary rocks are comparable to the temperature gradients predicted from the CPD mapping. Unfortunately, water samples were not collected for geothermometry analysis from these wells.

Table 1. Information on seven temperature gradient wells investigated as part of the research program. Group A wells were drilled by YGS. Group B wells were drilled by other parties. Wells drilled into granitoid rocks show lower temperature gradient values. A * indicates that the temperature measurements did not reach the bottom of the hole.

	Well name	Lat. (deg)	Long. (deg)	Well depth (m)	Temp. gradient depth interval (m)	Average temp. gradient (°C/km)	Bottom hole temp. (°C)	Rock type encountered
A	Takhini	60.8859	-135.3829	500	50-500	40	25.3	Sedimentary
	Ross River	61.9242	-132.5712	497	38-497	31	13.8	Sedimentary
	Duke River - DRGW	61.3684	-139.1628	221	110-200	37	4.7*	Sedimentary
B	Burwash Landing KFN-L	61.3536	-138.978	387	100-383	49	16	Sedimentary
	Carmacks EY22-01	62.1315	-136.3696	720	150-410	30	14.8*	Sedimentary
	Carmacks Copper WC-002	62.34562	-136.70306	476	150-468	23	9.4*	Granitoid
	North Star NS12-18	60.62156	-135.04489	2000	67-640	25	17.1*	Granitoid

Mapping of radiogenic heat production data across Yukon revealed numerous locations with anomalously high values of heat generation in plutons and meta-plutonic rocks (Colpron, 2019). Specifically, the Yukon data compilation yielded 510 samples (~25% of the database) with anomalously high heat generation values of 3-10 μW/m^3. A smaller number of samples (35) gave even higher heat generation values >10 μW/m^3. For comparison, typical granite has a heat generation value of ~2.5-2.8 μW/m^3 (Hasterok and Webb, 2017). In general, Eocene, Cretaceous, and Devonian plutons in Yukon show higher average heat generation values (Table 2). Paleocene and Precambrian plutons show heat generation values similar to the global average, while rock samples from all other time periods give heat generation values significantly below the average. Elevated heat generation values observed in Eocene, Cretaceous, and Devonian plutons suggests that plutons with those ages are more likely to have warm geothermal systems associated with them.

Table 2. Radiogenic heat production data for plutons and meta-plutonic rocks in Yukon. A = average radiogenic heat production and n = number of samples.

	Age	A (μW/m^3)	n		Age	A (μW/m^3)	n
Cenozoic	Miocene	n.r	0	Paleozoic	Permian	1.8	230
	Oligocene	0.7	2		Carboniferous	1.3	262
	Eocene	4.8	41		Devonian	4.4	72
	Paleocene	2.5	46		Silurian	n.r.	0
Mesozoic	Cretaceous	4.3	826		Ordovician	n.r.	0
	Jurassic	1.0	342		Cambrian	0.9	46
	Triassic	0.5	104		Precambrian	2.5	29

As part of the research program, new geoscience data collection included gravity, passive electromagnetic, and passive seismic surveys; they formed an integral part of subsurface characterization studies. These geophysical datasets were combined with existing aeromagnetic data, bedrock and surface geologic mapping, and water well data to construct 3D geological models at five Yukon communities. For three of these communities

(Burwash Landing, Watson Lake, and Teslin) the goal was to better understand geothermal potential along three major, crustal-scale fault systems in southern Yukon (Witter, 2020, 2022, 2023; Tschirhart et al., 2022). Additional subsurface characterization studies were completed at Haines Junction, to better understand a warm sedimentary aquifer geothermal system (Witter, 2024), and at the territorial capital, Whitehorse, to characterize the geothermal system feeding a group of warm springs (Witter, 2025). In general, the 3D geologic models: 1) helped refine fault mapping in the top few kilometres of the Earth's crust, where fracture-controlled permeability might allow the flow of deep geothermal fluids; 2) provided a structural framework to geologically interpret deep electrical conductors imaged by passive electromagnetic data; and 3) estimated depth-to-bedrock to identify potential warm sedimentary aquifers as well as cooler aquifers that could be exploited by geo-exchange systems. In addition, these subsurface characterization studies identified specific temperature gradient drill targets for low temperature (<100 °C) geothermal resources at all five communities.

3 DISCUSSION AND CONCLUSIONS

Key learnings from the Yukon geothermal research program include the following. First, elevated heat flow due to a thin crust in the northern Canadian Cordillera plus radiogenic plutons are the main drivers of geothermal heat in Yukon. Second, Eocene, Cretaceous, and Devonian plutons show the highest radiogenic heat potential. It is notable that nearly half of Yukon's thermal springs occur in proximity of radiogenic plutons. Third, temperature gradients are anomalously low when measured in holes drilled into unfractured granitoid plutons with low thermal conductivity and low radiogenic heat potential. These temperature gradients do not reflect the regional thermal gradient for the area. Fourth, average crustal temperature gradients predicted from Curie point depth mapping are largely consistent with temperature gradients measured in wells drilled into sedimentary rocks in southern Yukon. These temperature gradients likely do reflect regional thermal gradients. Fifth, community-focused geophysical surveying coupled with 3D geologic modelling has been an effective strategy for characterizing the geology and structure of the subsurface prior to selecting drill targets.

Additional geothermal research is needed in Yukon to better understand the geothermal resource potential. There are still many plutons in Yukon that remain unsampled. A more extensive pluton sampling campaign, followed by analysis of U, Th, and K could identify the locations of additional radiogenic plutons and possible thermal springs.

The Whitehorse trough is another region that merits further study because of the potential for hot sedimentary aquifers. It is a Mesozoic sedimentary basin that extends 650 km from northern British Columbia, past the territorial capital Whitehorse, to Carmacks in central Yukon. The depth, stratigraphy, structure, and temperature of the Whitehorse trough are poorly constrained due to a lack of deep drilling. Hot sedimentary aquifer-type geothermal systems in the Whitehorse trough are likely yet remain uncharacterized. Subsurface characterization and a deep exploratory well in the Whitehorse trough (to measure deep temperatures) are recommended due to the potential large size of hot sedimentary aquifers and the proximity to the capital city and main population centre.

In addition, geophysical surveys and 3D geologic models to characterize the subsurface at more Yukon communities followed by drilling of temperature gradient holes is important to understand geothermal potential in the population centres of Yukon. To reach below the influence of permafrost and long-term climate effects, temperature gradient holes ≥500 m deep are advised.

In general, due to the low population density of the territory, future geothermal exploration should be focused on the areas proximal to existing communities. As such, continued exploration and development of low temperature (i.e., <100 °C) geothermal resources for direct-use heating is recommended in southern Yukon, where most of the population resides, to take advantage of naturally elevated crustal heat flow, major faults, and radiogenic plutons. Development of geothermal resources heated by radiogenic plutons in other parts of Yukon may also be feasible to provide direct-use heat for remote communities and industrial activities such as at mine sites.

The available geothermal information suggests there are limited opportunities for locating conventional geothermal reservoirs with sufficient temperature (≥120 °C) to generate baseload geothermal electricity within ~2 km of the surface. Drilling to significantly greater depths to reach higher temperatures would be necessary, which would incur much higher costs; such costs may not be justifiable due to the low population density of most of Yukon. However, recent advances in the reduction of deep drilling costs for next-generation geothermal systems may improve the economics of geothermal electricity development in Yukon (Akindipe and Witter, 2025). A local source of renewable, baseload electricity generation would be a significant benefit to provide power to the growing population as well as remote mining operations in the territory.

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