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Geothermal Energy Country Update - Canada

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ABSTRACT

Geothermal energy exploration, development, and research has been ongoing in Canada for several decades. The country's cold climate and the push to develop renewable energy sources have driven interest in geothermal energy. Despite this drive, regulatory complexities and competition with other relatively inexpensive energy sources with already installed infrastructure, have hindered development. As such, interest has grown then fallen several times with the energy economy, leaving projects at a standstill. As of January 2023, there are currently no power producing geothermal projects in operation in Canada. Many hot spring pool and spa complexes remain active and Canada is a leading country in the installation of ground source heat pumps (geoexchange systems). However, in the last decade, interest in deep geothermal systems has renewed and there are many new projects starting up across several provinces and territories. Also, projects that showed limited progress for many years, such as the Mount Meager, British Columbia, resource, have started to renew their developments. Research is also growing across prominent research groups and universities. Areas of focus include both building upon previous studies, such as thermal gradients and heat flow in sedimentary basins, as well as researching new methods and resources, such as ground-source heat pumps, closed-loop systems, integrated geothermal operations and hybrid systems including heat storage. Development is being supported by federal, provincial, and territorial governments through grants and development of regulatory frameworks. Although challenges still remain for Canada to develop its geothermal energy resources, project advances on several power and thermal projects, ongoing research, funding, and regulatory acts are all moving forward to support geothermal development.

INTRODUCTION

Canada has immense geological diversity, including cratons, sedimentary basins, Recent volcanism, mountains, and more. As such, there are many types of geothermal energy being considered across the country, such as conventional geothermal, closed-loop technology, ground source heat pumps, (Hickson et al. 2023) in addition to co-production of oil and gas, and other types of hybrid systems. As well, the variations in existing energy sources, population density, and proximity to infrastructure throughout the country has led to a diversity of geothermal energy projects and technologies. Canada's northern climate and extensive areas of permafrost creates both opportunities (very high heating loads and large Delta T) and challenges (such as permafrost and ground ice).

Canada is made up of ten provinces and three territories, each unique in terms of economics, population and geography as well as geothermal energy development. Some (such as Nova Scotia and British Columbia) have been areas of development and research for several decades (c.f., Hickson et al., 2020), while others are just beginning to consider geothermal energy as part of their energy mix. A map of Canada with the approximate locations of the projects and studies mentioned in this paper is shown in Figure 1.

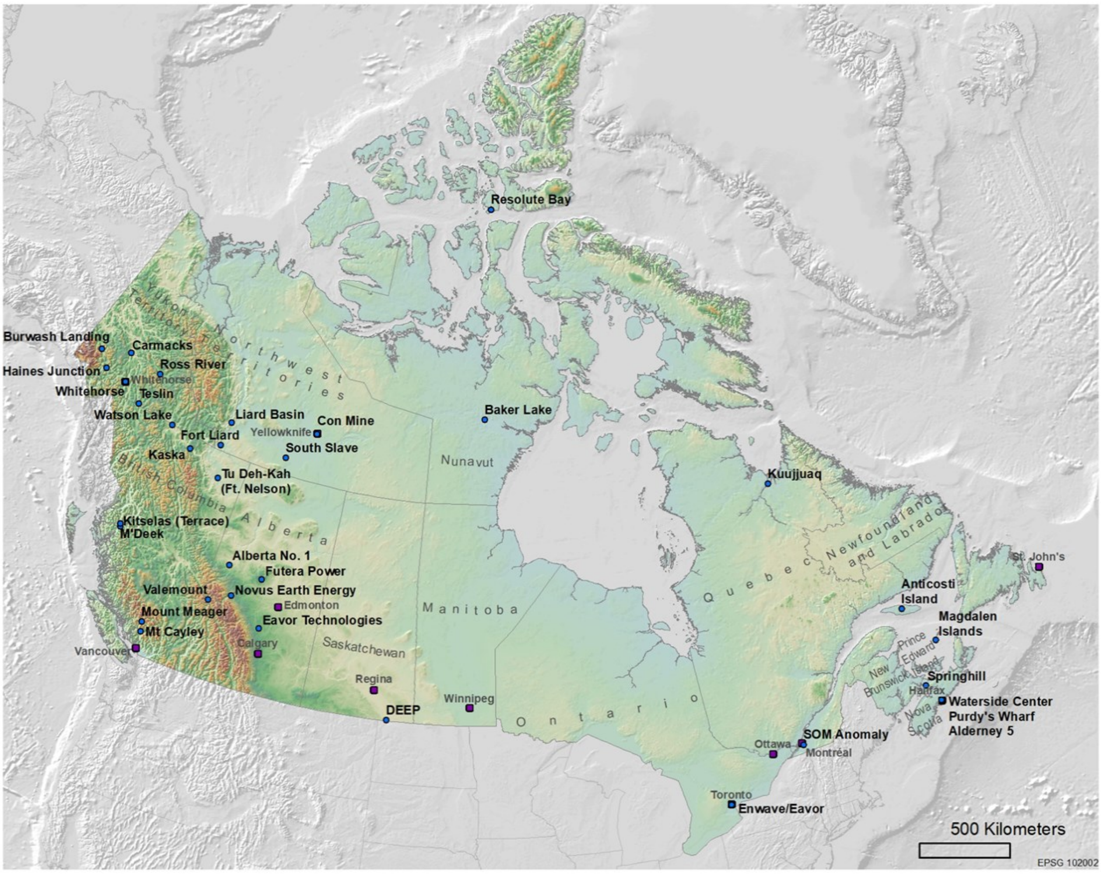

Figure 1. Approximate locations of industrial geothermal projects, research projects and ongoing studies in this review. Map courtesy of GEOSEIS, 2023.

1. GEOTHERMAL REGULATORY FRAMEWORKS AND ACTS

Canada's geothermal energy industry is still in its infancy. Only British Columbia (BC), Alberta and Nova Scotia have geothermal legislation in place. One issue has been clarity of what is defined as "geothermal" and how to differentiate between systems extracting naturally occurring heat and those that use either the ground or shallow aquifers or surface (or mine) water for heat storage and extraction (Hickson et. al., 2022). Geoexchange systems have a long history of use in Canada, and Canada ranks among the top nations in deployment of geoexchange systems per capita. Geoexchange system installation usually falls under groundwater regulations or other regulations dealing with surface construction and equipment (Ground Source Heat Pumps), whereas geothermal systems require a more specific regulatory regime (Hickson et al., 2022b).

In Canada, the development of resources is controlled by the individual provinces and territories. Most of the subsurface rights in Canada are owned by the "Crown". In provinces this is the Provincial Government and in Territories the Federal government. In some cases resource rights may be owned by the surface owners, but these cases are relatively rare. The subsurface rights are leased to corporations or individuals by the Crown. For this reason, each province and territory has developed, or is in the process of developing, its own regulations for geothermal development. Below is a summary of the provinces and territories that have, or are working on, geothermal regulatory frameworks.

1.1 British Columbia

Geothermal Resource Definition

Geothermal resource as defined in the *Geothermal Resources Act* "means the natural heat from the earth and all substances that derive an added value from it, including steam, water and water vapor heated by the natural heat from the earth and all substances dissolved in the steam, water or water vapor obtained from the well, but does not include: water that has a temperature of less than 80 °C at the point where it reaches the surface, or hydrocarbons"

Summary of Resource Tenure

- Resource is governed by fluid temperature.
- No multicommodity extraction permitted (e.g., hydrocarbons and/or mineral commodities, for e.g.,Lithium in brine).
- Rights are granted via public tender.
- Lease is one "Block" (as defined by Petroleum and Natural Gas Grid Regulation ~ 136 km^2).
- Rights are exclusive to a single owner.

1.2 Alberta

Geothermal Resource Definition

Geothermal Resources in Alberta are defined in both the *Mines and Minerals Act* and in *Bill 36: Geothermal Resource Development Act* as “the natural heat from the earth that is below the base of groundwater protection”. Of note in this definition is the reference to natural heat from the earth and exclusion of any reference to subsurface fluids produced from a subsurface reservoir and any constituents dissolved in those produced fluids. Further, the geothermal resource as defined in Alberta occurs only below the base of groundwater protection. Alberta’s geothermal act was just made into law on December 31, 2021 after a multiyear drafting and consultation process. Bill 36 is heavily based on Alberta’s existing Oil and Gas regulations and does little to directly support geothermal development (Hickson et al., 2022a)

Summary of Resource Tenure

- Resource is governed by heat.
- Multicommodity extraction permitted (but appropriate rights must be held, such as PNG rights for hydrocarbon extraction).
- Rights are granted via application.
- Lease is 9 sections, all of which must be laterally or diagonally adjoining.
- Rights are non-exclusive to a single owner (i.e., the current legislation has not defined how multiple geothermal operators may operation in a single locality; this is seen as a major failing of Bill 36 (Hickson et al., 2022a) .

In August 2022, the Alberta Energy Regulator (AER) released Directive 089: Geothermal Resource Development, which sets out the requirements for geothermal resource development below the base of groundwater protection. In other words, the rules, such as well designs, drilling activities, etc., under which geothermal development can take place.

1.3 Saskatchewan

Geothermal Resource Definition

“Geothermal Resource” is not yet defined in Saskatchewan legislation. Some guidance is available however through the Government’s Integrated Resource Information System – the platform through which various applications may be submitted, including for Storage Project Applications which appear to be the vehicle for a Geothermal project. In the Integrated Resource Information System, a geothermal project is defined as: “A geothermal project means a development where geothermal energy is recovered through deep well(s). There are two main types of geothermal project: open-loop and closed-loop. An open-loop system includes: (1) withdrawing formation water for the purpose of extracting geothermal energy as part of an industrial process, and (2) disposing of the cooling fluids into subsurface following the extraction of its heat content. In a closed-loop system, the source fluids are circulated in a sealed wellbore – heat exchange loop and there are no formation fluids to be withdrawn or fluids to be disposed. The geothermal project application is only applied to the subsurface activities.”

Based on this definition, an open-loop geothermal operation is a reasonable fit with the concept of a “Storage Project Application”.

In a Government Guidance document on regulation of disposal wells, geothermal projects are defined as: “A geothermal project means a development that geothermal fluids are produced from a water source well, the geothermal energy is recovered at surface as part of an industrial process for any purpose, and the cooling fluids are disposed of into subsurface through a waste disposal well.”

Again, this definition seems well-suited to an open-loop geothermal scheme but not a closed-loop operation which has no need for disposal, other than while drilling operations are underway.

Summary of Resource Tenure

- Resource is governed by pore space.
- No multicommodity extraction permitted.
- Rights are granted at government discretion.
- Leases size is not defined.
- Rights are exclusive to a single owner.

1.4 Quebec

After some period of inertia, geothermal energy, beyond ground-source heat pumps, is receiving increasing attention within Quebec’s Province. The term ‘deep geothermal energy’ was mentioned for the first time in a new *Bill: ‘’Loi visant principalement à mettre fin à la recherche et à la production d'hydrocarbures ainsi qu'au financement public de ces activités’’*, which was adopted in 2022. This new bill is an important step taken within Quebec’s energy transition plan since it aims at ending the exploration for and production of hydrocarbons and ending public financing of those activities. Furthermore, this new bill authorizes the implementation of pilot projects to acquire geoscientific knowledge relating to, among other topics, deep geothermal energy potential. The Institut national de la recherche scientifique (INRS) submitted a memorandum at the time consultations were made to improve the law and suggested to better define regulations for pilot geothermal projects (Gascuel et al., 2022). INRS continues to work in close relation to the Ministère de l’Économie, de l’Innovation et de l’Énergie to assess the potential of converting suspended oil and gas wells into ground heat exchangers to harness geothermal resources. Shallow resources associated to geothermal heat pump resources remain regulated through the ‘’Règlement sur le captage des eaux souterraines’ of the ‘’ Loi sur la qualité de l’environnement’’.

1.5 Nova Scotia

Nova Scotia was and early adopter of geothermal legislation, in part because of the Springhill Mine (Figure 1) and the province's experience with oil and gas operations. In 2016, *Bill No. 149: Mineral Resources Act* was passed.

Geothermal Resource Definition

The purpose of the Act is to "support and facilitate responsible mineral resource management". Both minerals and geothermal energy are included as mineral resources. The Act defines a geothermal resource as: "a substance, including steam, water and water vapour, that is found anywhere below the surface of the earth and that derives an added value from the natural heat of the earth present in, resulting from or created by the earth".

Summary of Resource Tenure

- All minerals are reserved to the Crown
- A "geothermal resource area" is designated by the Governor in Council
- A royalty regime is provided for mineral resources

1.6 Yukon

In 2020, the Government of Yukon released *Our Clean Future: A Yukon strategy for climate change, energy and a green economy*. This document outlined actions the Government of Yukon would take to address the impacts of climate change while building a green economy and ensuring Yukoners could access reliable, affordable and renewable energy. One action the government committed to was developing a *Geothermal Resources Act (Action E11)* that would regulate geothermal energy development in the territory to help reduce Yukon's reliance on fossil fuels and meet its needs for electricity and heat.

A public engagement process was hosted by the Department of Energy, Mines and Resources through an open, direct call for submissions. The purpose of this engagement was to gather feedback regarding new geothermal legislation and ensure the public had an opportunity to identify and contribute to key aspects under legislative consideration. During this phase, direct feedback was received from non-governmental organizations, industry representatives, First Nations, various levels of government and members of the public from Yukon, western Canada, and Iceland. The engagement period ended in September 2022. Following, the Government of Yukon will be publishing a *What We Heard* report based on the submissions from the public. Overall, the feedback received was positive with a strong support for the development of geothermal resource legislation in the territory. Policy and regulatory framework considerations that received the most interest and input pertained to the definition of geothermal resources; regulatory regime considerations; royalty structures; and issues surrounding decommissioning and reclamation. A significant number of stakeholders wanted to clearly state their willingness and interest to work with Indigenous governments and communities to ensure positive and productive collaboration in any future geothermal resource projects.

This feedback further reinforced the Government of Yukon's interest and commitment to the development of geothermal resource legislation and ongoing government to government discussions involving Indigenous communities that may be potentially affected by any potential geothermal exploration and development. It also further informed and identified options to create a conducive investment environment that would encourage geothermal development in the territory. The legislative framework will continue to be developed through 2023

1.7 Northwest Territories

In 2010 the Government of Northwest Territories – Department of Environment and Natural Resources (GNWT – ENR) commissioned the Pembina Institute to compete an inter-jurisdictional review of geothermal energy legislation and policy (Holroyd and Dagg, 2011); however, this report did not result in further activity toward development of a geothermal regulatory framework.

In 2018 the GNWT released its *2030 Energy Strategy*, which identified geothermal energy as one potential component of the government's strategy toward GHG emission reduction and development of secure, affordable, and sustainable energy in the Northwest Territories (NWT). In the same year, the GNWT also released the *2030 NWT Climate Change Strategic Framework*, which outlined the Government's goals to transition to a strong, healthy economy that uses less fossil fuels and reduces GHG emissions, increases the understanding of climate change impacts in the NWT, and builds resilience and adaptation to a changing climate. These Government goals spurred a renewed interest in geothermal energy in the NWT, leading to renewed interest in geothermal energy regulatory frameworks.

The GNWT realizes that much has changed on the global scene in the decade since the report by the Pembina Institute, so in 2021 a new report was commissioned to the University of Calgary's School of Public Policy – Extractive Resource Governance Program (Hickson et al., 2022b). This report is anticipated to be released publicly as a peer-reviewed Open File by the Northwest Territories Geological Survey, and to be a first step toward the development of a tailor-made geothermal regulatory framework for the NWT.

1.8 Other Jurisdictions

All other jurisdictions are currently treating geothermal and geoexchange projects on a case-by-case basis. In most cases existing drilling regulations under water resources acts or other resource extraction regulations (e.g., diamond drilling for mining exploration and development or hydrocarbon extraction) are being used. In the case of Geoexchange projects, construction regulations and regulations pertaining to boring geotechnical bore holes are typically used. Environmental regulations are also being treated on a case-by-case basis.

2. PROVINCE AND TERRITORY UPDATES

2.1 British Columbia

Exciting progress has been made on geothermal energy exploration and development projects across British Columbia (Figure 1). Indigenous communities and private developers are taking an active leadership role in advancing exploration of geothermal resources in both volcanic settings and development of sedimentary hosted geothermal resources. In Canada, British Columbia has been leading the nation in terms of advancing geothermal investigations, building on the early researchers (c.f., Fairbank and Faulkner., 1992) and later detailed technical and economic work by Kerr Wood Liedal (2015) on power generation and Hickson et al. (2016) on direct-use applications. A summary of key project progress is provided below.

Mount Meager

Geoscience BC (GBC), an arms-length entity from government, is a not-for-profit geoscience organization, and has had a Geothermal Technical Advisory Committee since 2010. In 2019, GBC contributed CDN$500,000 in funding along with provincial and federal contributions to a new project in the Garibaldi Volcanic Belt (Figure 1; Grasby 2019; Geoscience BC 2019). This belt, which includes Mount Meager, will be the focus of reducing the exploration risk in one of the regions with the highest geothermal potential of Canada. In 2021-22, Phase 2 of the GBC study focused on the Mount Cayley area, including field mapping and data collection. The Phase 2 final report will summarize geothermal potential of the Garibaldi Volcanic Belt utilizing findings from both research Phases (Grasby et al. 2022). An online community open house was hosted in August 2021 by GBC, led by Dr. Steve Grasby of the Geological Survey of Canada to provide an update on the Garibaldi Geothermal Volcanic Belt Assessment (Grasby et al. 2022).

In addition to the research efforts by the Geological Survey of Canada in the Garibaldi Volcanic Belt, and previous studies from Geoscience BC, there are two active geothermal leases in the Mount Meager area. This region has seen intermittent geothermal exploration over the past half a century with reports of temperatures exceeding 260 °C downhole. However, the permeability found in the young rocks of the region during historical exploration efforts was insufficient to produce electricity economically. Oncoming developers are planning to apply modern exploration methods and drilling technologies to increase the likelihood of finding hot and highly permeable subsurface zones. The south lease is owned by Meager Creek Development Corporation, a private developer aiming to produce green hydrogen from geothermal energy. The north lease is owned by Tecto Energy, which aims to generate electricity from the geothermal resources underneath.

The Meager Creek Development Corporation's project is located 70 km northwest of Pemberton, BC on the Coast Mountain Range as shown in Figure 2 below. The project is accessible via existing forest service roads; minor upgrades will be required in 2023 prior to the drilling target timeline of Q3 2023. Meager Creek Development Corporation holds the geothermal lease over an area 4,270 hectares, which allows for exploration and development of geothermal resources (Meager Creek Development Corporation, 2022).

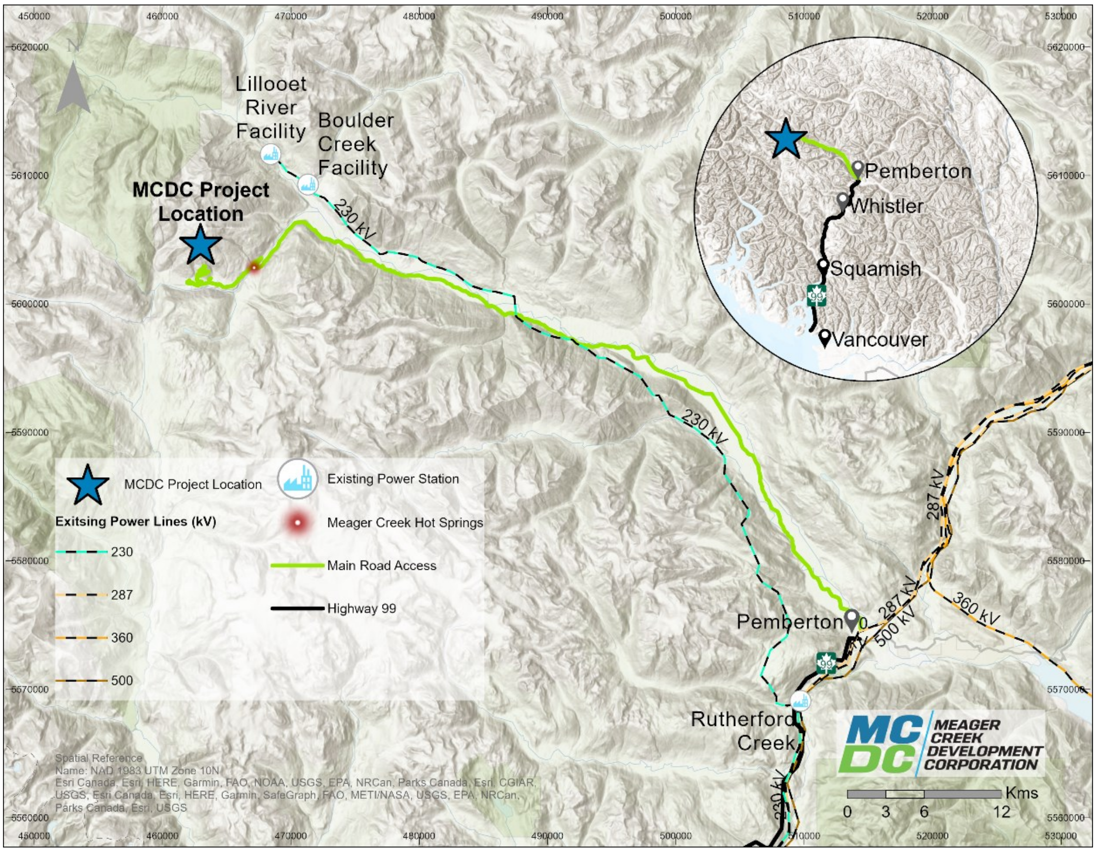

Figure 2. Mount Meager: Map of Meager Creek project location (Meager Creek Development Corporation 2022)

Tu Deh-Kah

In northeast British Columbia, the Clarke Lake depleted natural gas reservoir (Figure 1) is being redeveloped for its geothermal energy potential. The Clarke Lake Reservoir, within the Western Canada Sedimentary Basin, is the oldest and amongst the most abundant gas fields in British Columbia and after 60 years of production is losing commercially viable due to high water cuts. The reservoir is located adjacent to the town of Fort Nelson, a northern Canadian town with long cold winters. The Indigenous people of the region, the Fort Nelson First Nation (FNFN), are the project proponent. The FNFN re-named the project in August 2021 using their traditional Indigenous language to the Tu Deh-Kah (TDK) geothermal project. The project has received significant funding support from federal and provincial grant programs, most notably the Emerging Renewables Power Program (ERPP) through Natural Resources Canada (NRCan) a Federal Government department.

The TDK project aims to generate 7-10 MWe in net electrical generation utilizing binary Organic Rankine Cycle (ORC) technology, with commercial operation anticipated in early 2026. In addition to power generation, direct-heat use and cascading geothermal opportunities are being investigated. A likely direct-heat use in this northern, remote, cold community is to utilize geothermal heat in contributing to food security through agricultural and/or greenhouse development. In 2021 and 2022, the BC Ministry of Energy, Mines and Low Carbon Innovation granted the TDK project proponent two Geothermal Exploration Permits over an area of approximately 13,400 hectares, across the extent of the target geothermal reservoir reef sequence as shown in Figure 3 below, granting TDK rights over to investigate and develop the geothermal resource in the area.

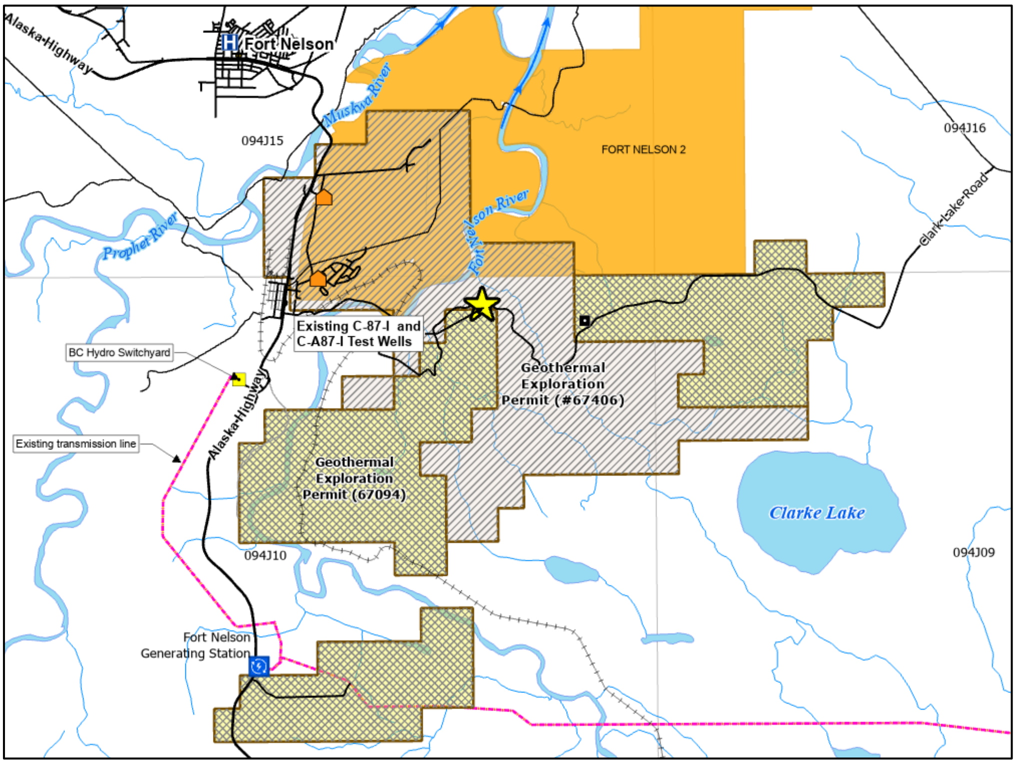

Figure 3. Tu Deh-Kah: Overview of geothermal exploration permit areas and C-A87-I well test site (Barkley Project Group 2022)

Based on the abundance of existing well data, Phase 1 of the project, geothermal exploration, was already complete at the outset of TDK Project development in 2019. Phase 2 of the project was completed in 2020 and included major geoscience investigations and conceptual reservoir modelling of the geothermal resource as well as background investigations into social and environmental concerns of the geothermal development. Phase 3, completed in 2021, included drilling and completing the TDK geothermal test well, along with the deepening and refurbishment of an existing gas well, in 2021. This TDK well doublet consists of a full-sized geothermal producer along with a repurposed natural gas well serving as a temporary re-injection well for testing purposes. Observations and data collected via well logs and temperature logs to date indicate that the geothermal resource quality in terms of temperature is as anticipated in the 120 °C range, and highly permeable target production intervals were encountered during drilling. The next major phase of work will include full well field drilling in 2024, followed by surface facility construction in 2025 and commissioning of the ORC power plant in 2026.

<u>Kitselas Geothermal (Terrace, BC)</u>

In the coastal northwestern region of British Columbia (Figure 1), Kitselas Geothermal Inc. is advancing its Fuel for Reconciliation project. through additional geophysical surveys and have received $500,000 in funding from the First Nations Clean Energy Business Fund. In August 2022, Kitselas Geothermal Inc. entered a partnership with Shell Canada to support de-risking and appraisal of the geothermal resource near Terrace, BC, targeting the M'Deek Reservoir. The Fuel for Reconciliation project is not focused on electricity generation, but rather direct heat uses. This project's larger vision is to decarbonize local industry to provide social, environmental, and economic benefits to the region and to the Kitselas First Nation. (Kitselas Geothermal 2022). The project will be developed in incremental phases, with initial focus on developing industrial scale geothermal heating. Progress has been made through exploration and planning stages. In 2020, 4 pilot core holes were drilled, and 3 additional core holes were drilled in 2021. Reservoir modelling is currently underway to support production well target selection (Kitselas Geothermal 2022).

Figure 4. Kitselas Geothermal Project: Conducting measurements of a hot spring in the Lakelse Lake area (from Kitselas Geothermal Inc.)

Kaska Dena

Led by the Daylu Dena First Nations Council, early phase geothermal exploration is underway in Kaska Dena territory of north central British Columbia (Figure 1), where heat flow and geothermal gradients are notably above average values (Grasby et al. 2012; Figure 5). This region is not well serviced by existing electrical infrastructure and is highly dependent on trucked-in fossil fuels for the energy needs of its communities. While geological data for this region is limited, as it has not been the focus of historical geothermal exploration programs, deep continental scale faults co-located with Quaternary volcanism and Cenozoic sedimentary basins may hold geothermal resources of yet unknown quality (Witter 2020). This exploration program will provide geothermal-specific data for this region of northern BC, while creating local capacity and employment opportunities.

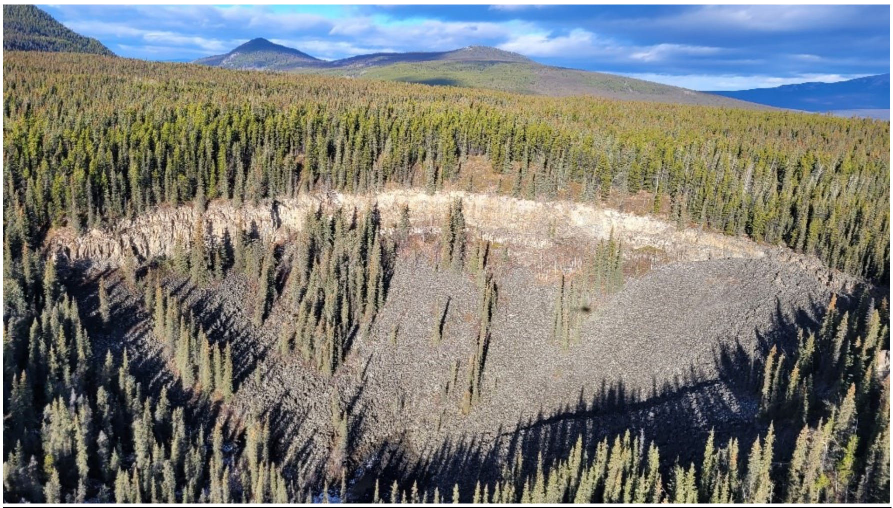

Figure 5. Kaska Nation: Pliocene-Holocene basalt outcrop in the Kaska Nation territory.

2.2 Alberta

Novus Earth Energy

Novus Earth Energy, a Calgary-based geothermal company, announced the Latitude 53 Project located near Hinton, AB in early 2022 (Figure 1). The project has garnered attention and support from surrounding communities, as well as all levels of governments, and industry. The enthusiasm for the Latitude 53 Project stems from the potential direct-use opportunities, which include use of thermal and electrical energy for agriculture.

Using Novus Earth's efficient closed-loop well design, the connection of geothermal direct energy use to closed environment agriculture (CEA) addresses growing food security concerns and GHG reduction goals. Compared to traditional agriculture, CEA uses less water, has a smaller land footprint and mitigates the impacts of extreme weather events. CEA is energy intensive, using LED lamps instead of/coupled with sunlight, HVAC air-conditioning to control temperature and water-filtration systems to re-use water, which all require a significant energy load. Novus Earth is addressing these concerns using their proprietary advanced geothermal system to extract heat and produce electricity, making CEA and food security both sustainable and economical.

Novus's subsurface geothermal loop system provides reliable energy with over 97% operating times, to meet varied needs and is replicable in many global locations. Novus's Latitude 53 Project is progressing with commercial geothermal well drilling anticipated for Q3 2023.

Alberta No. 1

Alberta No. 1 is a planned combined power and direct heat use project in the Municipal District of Greenview, south of Grande Prairie, AB (Figure 1; Hickson et al., 2021). In 2019, Alberta No.1 was awarded $25.4 Million of matched funding by NRCan's ERPP to develop a geothermal power plant. Target formations are Devonian-aged limestone units that have been hydrothermally altered to dolomite, as well as interbedded sandstone units. Specifically, the target formations span from the top of the Winterburn Group to the base of the Granite Wash Formation, which overlies the Precambrian Basement.

In 2021, Alberta No. 1 conducted a temperature log on an idle disposal well. These indicate that temperatures above 120°C are attainable at depths of 3,500 m and below (Figure 6). As well, the results suggest two distinct thermal gradients within the sedimentary sequences: the upper clastic sequences have a thermal gradient of approximately 31 °C/km, while the underlying carbonate sequences have a lower thermal gradient of around 22 °C/km (Huang et al., 2021). These results have important implications for the understanding of geothermal resources within the WCSB, as well as interpretation of oil and gas temperature data.

After some time working with the government and AER as they developed both *Bill 36: Geothermal Resource Development Act* and the AER's *Directive 089,* Alberta No. 1 is now able to apply for the necessary licenses for development (Hickson et al., 2022b)

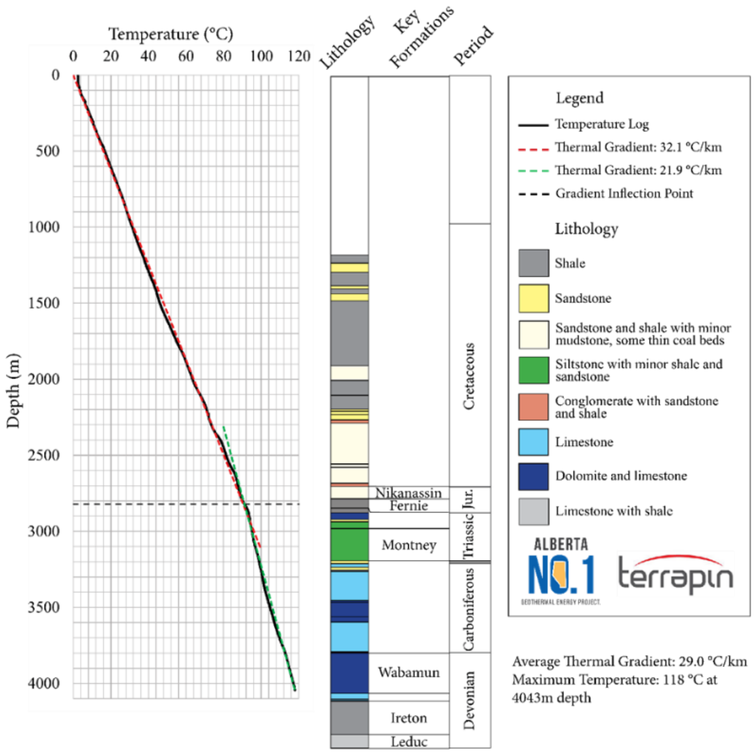

Figure 6. Alberta No. 1: Temperature-depth profile and lithology log of the well that the temperature log was run.

FutEra Power

FutEra Power Corp. (FutEra), based in Calgary, AB, has begun construction on a co-production natural gas/geothermal power plant near Swan Hills, AB (Figure 1). They plan to have approximately 30% of the 21 MW power generated by the plant to come from geothermal energy. The conversion of the existing natural gas power plant to co-production will utilize only the existing surface footprint. Brine of 100 °C from the existing Swan Hills oil and gas wells will be used in conjunction with the exhaust heat from the natural gas turbines to power the Organic Rankine Cycle portion of the power generation (Figure 7). They expect to have the geothermal power portion onstream by the end of 2023.

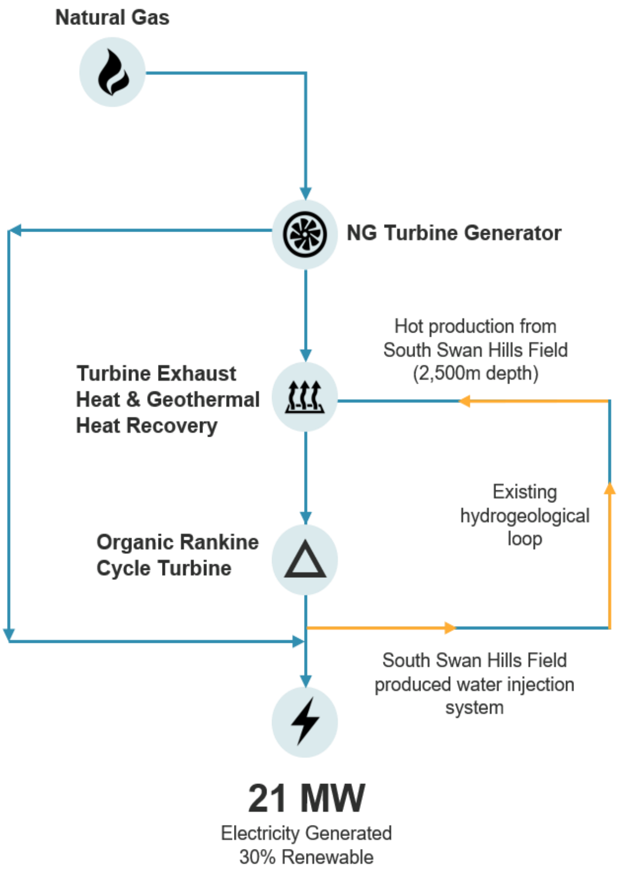

Figure 7. FutEra Power: Schematic outlining the co-production power process.

Eavor Technologies Inc.

Eavor Technologies Inc. (Eavor) is an Alberta-based geothermal technology company and the developer of the Eavor-Loop™ technology, a closed-loop geothermal system that provides a novel solution that enables scalable, baseload or dispatchable, emissions free electricity to be generated next to demand. The closed-loop technology is a buried-pipe system, akin to a deep radiator or heat exchanger. The working fluid is composed primarily of water added at surface, which is then circulated to harvest heat from deep in the earth to generate electricity, used for commercial direct heating, and/or utilized for cooling applications.

Eavor's technology demonstration project in Central Alberta, near Hinton (Figure 1) continues to produce with <0.3 m^3/day leak off and within 2% of the predicted thermal output of 800 kW_{th}. Eavor broke ground on its first commercial implementation of the technology in October 2022 and is predicted to spud June 2023 in Bavaria, Germany. This project will tie into the electric grid and has the potential to become a combined heat and power project once the appropriate heat infrastructure is built in the nearby town of Geretsried. In addition to the Bavaria project, Eavor has signed a heat purchase agreement with enercity in Hannover and is in the design phase of that project.

Eavor concluded the 'Eavor-Deep™' test well in New Mexico in December 2022, which reached depths > 5 km and temperatures in excess of 200°C, validating numerous aspects of the second-generation technology. This technology focuses on drilling deeper and hotter compared to the horizontal drilling technologies being deployed in the Bavaria or Hannover projects.

On the Canadian front, Eavor is collaborating with Enwave for a district heating project in Toronto, Canada, and with Eavor Yukon on an electricity project. The Yukon project also involves partnerships with the Little Salmon Carmacks First Nation. Eavor Yukon has been active in the data gathering stage and has re-entered numerous deep mining holes to obtain bottom hole temperature data. They have also drilled one diamond drill well near the Whitehorse Trough in late 2022.

2.3 Saskatchewan

While sedimentary basins such as the Williston Basin may not have the higher temperatures found in volcanic-hosted geothermal resources, they do have some advantages relative to other geothermal regimes. The reservoir properties and extents are better understood, aided by decades of oil and gas development, which de-risks early-stage exploration. Additionally, sedimentary reservoirs often have suitable permeability thickness and storage for high fluid production volumes needed for binary (ORC) geothermal power plants.

Currently, there is one project in the province operated by Deep Earth Energy Production Corporation (DEEP) which is located in southeast Saskatchewan, a few kms north of the Canadian/United States border (Figure 8).

Deep Earth Energy Production Corporation (DEEP)

DEEP is leading the way in Canada with plans for construction of a geothermal power facility (Figure 1). This will introduce baseload renewable power generation for the first time to the SaskPower grid. This project will use innovation, proven technology, and a highly skilled workforce to develop and construct Canada's premier geothermal power facility with a long runway for further expansion. After more than a decade of preliminary work and preparatory engineering, supported by $25.6M ERPP NRCan (Natural Resources Canada) funding, DEEP is positioned to be the first producer of large-scale geothermal power in Canada. DEEP has geothermal rights within 39,120 hectares (approximately 100,000 acres) with the potential for approximately 200 MWe of geothermal power.

The geothermal resource is a naturally occurring >120 °C 3,450 m deep aquifer at the base of the Williston Sedimentary Basin. DEEP's drilling and extensive well testing of six of the deepest wells ever drilled in Saskatchewan, from 2018 to 2021, have demonstrated that the basal sands of the Deadwood Formation can be a viable geothermal electrical generating and direct heat resource for the province. A made-in-Saskatchewan energy opportunity, the province has a highly supportive and streamlined regulatory environment thanks to 60 years of oil and gas development and mining operations.

In 2021, extended well testing of the geothermal system was completed. Hot brine was produced from the horizontal well and injected into previously drilled vertical wells. This large volume production and injection loop test was used to refine the reservoir model and determine optimized horizontal well lengths and spacing.

DEEP has developed a unique geothermal field design to manage the reservoir, balancing reservoir pressure, heat extraction and subsequent reheating of the injected brines, using horizontal production and injection wells (Figure 9). DEEP's 'ribcage' geothermal well field design is globally unique and may be a transformative application of modern oil and gas drilling and completions techniques applied for the first time on a renewable energy project. DEEP will tap into the geothermal energy stored in a permeable sandstone layer within the Deadwood Formation. This sand was deposited on the Precambrian basement rock during the Cambrian Period, approximately 500 million years ago.

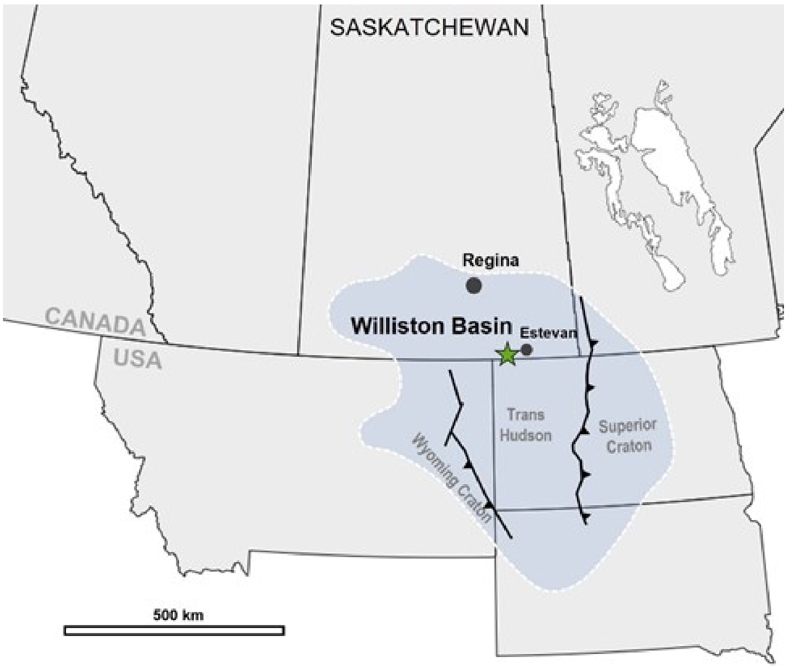

Figure 8. DEEP: Map showing location of DEEP project (green star) within the Williston Basin in Southern Saskatchewan.

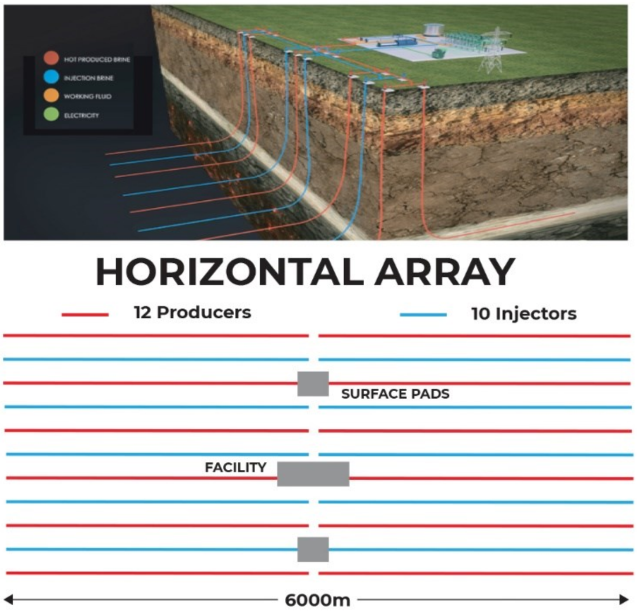

Figure 9. DEEP: Ribcage geothermal well design.

2.6 Quebec

Ground-source heat pumps (GSHP) (GeoExchange systems (Hickson et al., 2022c) the sole geothermal technology used in the province of Quebec at the present time. Although efforts were made by the Institut de recherche d'Hydro-Quebec (IREQ) and the Institut national de la recherche scientifique (INRS) to evaluate the electricity production potential of deep geothermal energy in southern Quebec and Eastern Canada (Bédard et al., 2016; Richard et al., 2016), the conclusion was that the identified sites were generally not appropriate for a large-scale pilot project in the current context of low electricity prices. The reasons are mostly the required depths, the uncertainty over the temperature, and the risks associated with deep reservoirs (Figure 10). Nevertheless, IREQ's report highlights that a significant reduction in deep drilling costs and the development of expertise in the creation of geothermal reservoirs could potentially pave the way and help the deep geothermal sector to grow in Quebec.

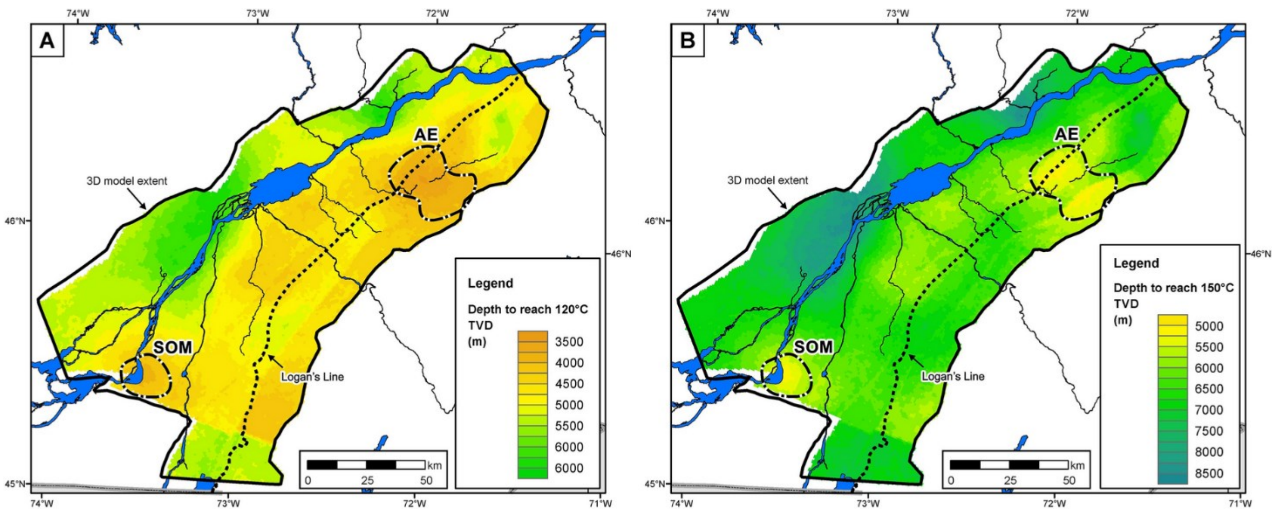

Figure 10. Quebec Research: A) Depth to reach 120 °C and B) depth to reach 150 °C (Bédard et al., 2020). SOM – Southeast of Montreal anomaly, AE – Arthabaska-Erable anomaly, TVD – true vertical depth.

In October 2022, a 400 m deep well was drilled by Acti-Cité in the town of La Prairie, south of Montreal. This site is within the limits of the Southeast of Montreal (SOM) anomaly (Figure 1). An eco-neighborhood is being developed in an old quarry site at La Prairie, and geothermal could be an option to provide space heating through a deep geothermal district heating system or through geothermal heat pumps. INRS is evaluating the geothermal gradient and the geothermal potential of the site. This 400 m slim hole well is also enabling the collection of more information to support the existence of the SOM anomaly.

Another important venture in Quebec is the first geothermal pilot project installed in Kuujjuaq, the regional capital of Nunavik (Figure 1), which is the Inuit region in northern Quebec (above 55th parallel). This project is a 30-kW horizontal GSHP system (Figure 11) installed for the community's swimming pool facility (Giordano and Raymond, 2020).

Figure 11. Kuujjuaq: Geothermal pilot project 30 kW horizontal GHSP system for Kuujjuaq, Quebec community swimming pool.

This geothermal pilot project is a result of the "Generating New Opportunities: Indigenous Off-diesel Initiative" (IODI). This initiative aims to support remote Indigenous communities in developing and implementing plans to reduce diesel consumption for heating and power purposes. The IODI is a program funded by Natural Resources Canada to support Clean Energy Champions and their communities with tailored clean energy training, access to expertise and financial resources to develop and start implementing an ambitious diesel reduction plan. This project is a first demonstration for GSHP operation in a subarctic climate.

Within the same IODI program, a 240 m deep slim hole was drilled nearby Kuujjuaq's Forum building. This well was drilled as part of a drilling training class supported by Avataa Explorations Logistics Inc. with the goal of installing a 145 m deep vertical closed-loop GSHP. The Kuujjuaq Forum is operated by Kuujjuamiut Inc and features three main facilities that continue to operate on a daily schedule: an ice arena, a gymnasium, and a fitness center. The main heating fuel used in this building is diesel and the shallow geothermal system is expected to extract 9.4 ± 0.8 MWh of energy annually (Géotherma Solutions Inc., 2022). This 240 m deep well also made possible to advance the stage of knowledge about Kuujjuaq's deep geothermal energy potential. A geothermal gradient of about 21 °C/km was evaluated, suggesting a surface heat flux of 57 mW/m^2 (Miranda and Raymond, 2022). Such values suggest that at a depth of about 2-3 km, the thermal energy in-place may be sufficient to provide space heating for this community.

2.7 Nova Scotia

A number of homes and institutional and commercial facilities throughout Nova Scotia have groundwater and ground-source heat pumps installed. One of the most famous geothermal systems under operation in Nova Scotia is the one installed in the abandoned mines of Springhill (Figure 1). These flooded former coal mines contain about 4,000,000 m^3 of water which is recovered at the surface at a temperature of about 18 °C (Jessop, 1995). The water is used as the input to heat pumps for heating and cooling industrial buildings. Such a system can provide lower heating costs than heating by fuel oil, while also reducing carbon dioxide emissions. The systems, initially deployed in Springhill in 1989 for a single building, have in recent years expanded to a geothermal business park, supplying many buildings (SaltWire, 2019). Beyond Springhill, the Purdy's Wharf in Halifax was the province's first large-scale project to use temperate differences in the ocean for cooling (Nova Scotia, 2022). Finally, the new Waterside Centre in Halifax will also use seawater to heat and cool (Nova Scotia, 2022).

Since 2020, a collaborative program has been underway in Nova Scotia by Net Zero Atlantic to assess the deep geothermal resources in the onshore of the province. Phase I of this project had four main goals (Comeau et al., 2020). The first was to provide a review of the general types of geothermal resources in Nova Scotia (excluding shallow resources utilized by ground-source heat pumps), with reference to key regional, national, and global examples. The second objective was to provide a preliminary evaluation of the potential and favorability for geothermal electricity generation and heat production across the province. The third goal was to recommend next steps to further de-risk targeted areas. The fourth objective was to describe the economic case for potential geothermal resource exploration and development in the province.

The Phase I report (Comeau et al., 2020) concluded that there are areas in Nova Scotia with a relatively high geothermal potential for electricity generation and that most of the province's sedimentary basins may have geothermal potential for direct-use of heat (Figure 12). Additionally, the Phase I report also suggests that new and emerging technologies may be promising to expand the extent of the areas of Nova Scotia that may be considered for direct-use and electricity geothermal development. Finally, interesting opportunities can also be found within the abandoned coal mines for space heating and cooling.

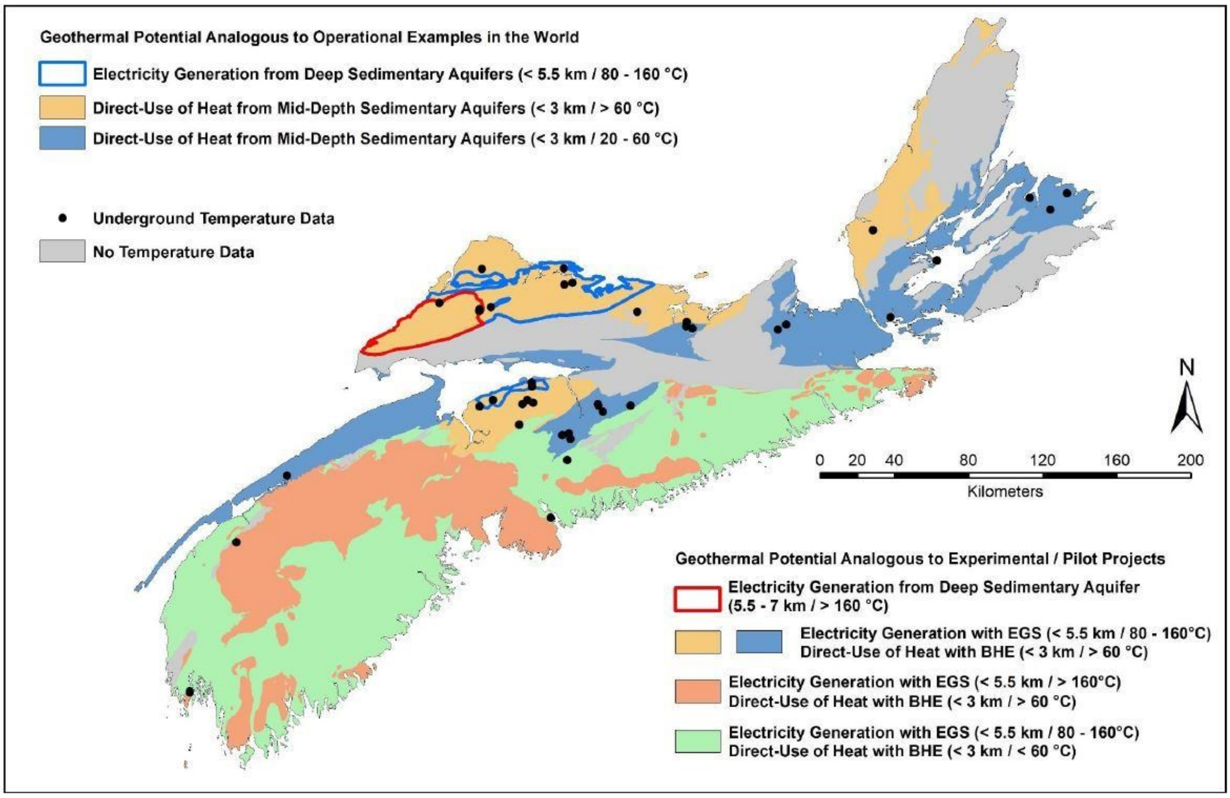

Figure 12. Net Zero Atlantic: Geothermal potential in Nova Scotia for electricity generation and direct-use of heat, based on similar operational examples around the world (Comeau et al., 2020).

Phase II of Nova Scotia's geothermal collaborative program had the objective of assessing the technical and financial suitability of deep geothermal systems for specific heating applications in three specific potential areas in the province (Malone, 2021). The report suggests that deep geothermal systems may not be cost-effective under base case scenarios for the archetype buildings studied (greenhouses, aquaculture, and district heating). However, there are still many unknowns. Both Phase I and Phase II highlight that more subsurface data needs to be gathered in Nova Scotia to fully assess the province's potential. The reports suggest that exploration wells drilled in geologically preferred settings and in commercially viable locations are required to de-risk the province's mid-depth geothermal resources. Thus, in 2022, Phase III of Nova Scotia's collaborative program aimed at providing a forward-thinking strategic planning study to recommend specific activities to support a successful drilling campaign (Borealis GeoPower Inc, 2022).

2.8 Yukon

The Yukon Geological Survey (YGS) initiated a geothermal research program in 2016 that aims at evaluating the geothermal energy potential of Yukon (Figure 1). Although the bulk of Yukon's power is generated from renewable sources (mainly hydro, with increasing components of solar and wind), the rapid population growth and potential new mine developments are increasing power demands and the reliance on hydrocarbon-powered generators to meet the demand. Although the power grid is currently over 90% renewable, four communities are off-grid. Further, the majority of Yukon homes and businesses are heated with hydrocarbons, which are all trucked from the south.

Yukon Geological Survey Research

Initial studies by YGS involved mapping the Curie Point Depth (CPD) using aeromagnetic data (Witter and Miller, 2017; Li et al., 2017; Witter et al., 2018) and calculating the potential heat generation of granitoid plutons from lithogeochemical data (Friend and Colpron, 2017; Colpron, 2019). The CPD mapping indicates that higher heat flow could be expected in parts of southern Yukon (Figure 13A). The potential heat production calculations show that a number of granitoids have values in excess of average granite (~2.5 $\mu W/m^3$) with Late Cretaceous granites yielding strongly anomalous values >10 $\mu W/m^3$ (Figure 13B). Direct measurements of thermal gradient were obtained from two wells drilled by YGS near Takhini Hot Springs in the Whitehorse area and within the Tintina Trench near Ross River (Figure 1).

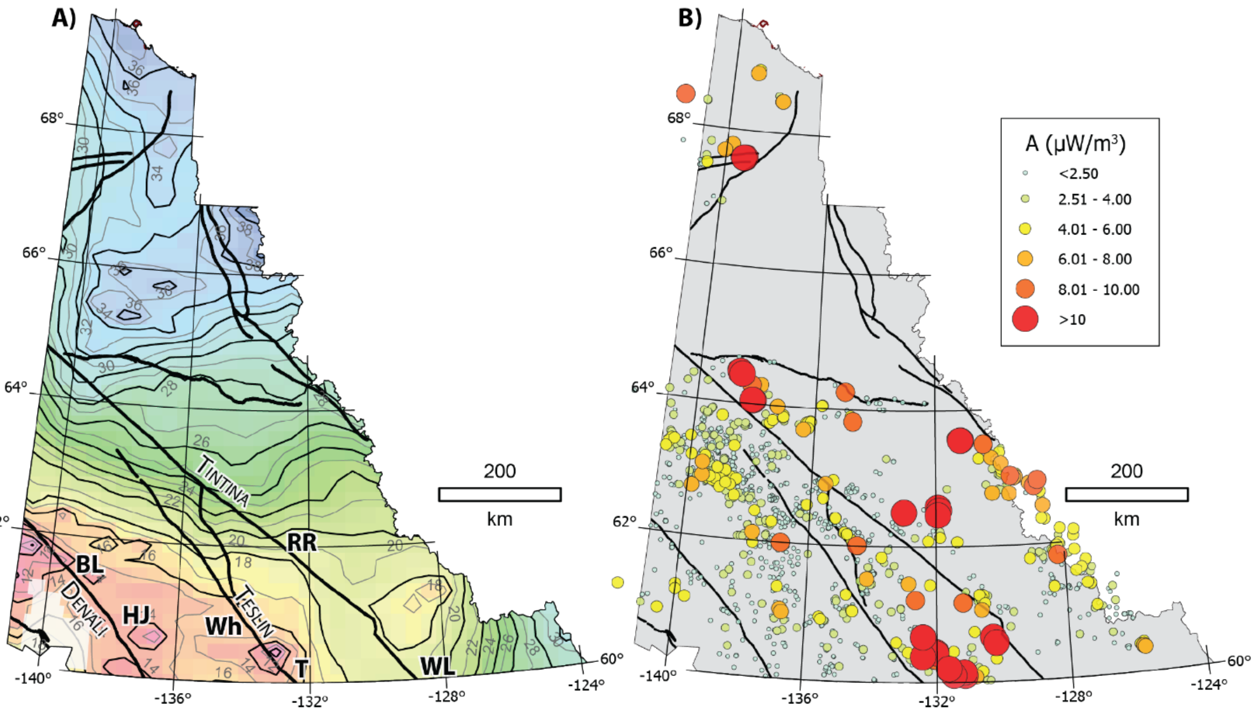

Figure 13. Yukon Geological Survey Research: A) Map of Curie point depth in Yukon (data from Li et al., 2017). Contour labels are in kilometres. Major faults are shown by bold black lines and those that are current focus of YGS studies are labeled. Communities mentioned in text are indicated: BL – Burwash Landing; HJ – Haines Junction; RR – Ross River; T – Teslin; Wh – Whitehorse; WL – Watson Lake. B) Potential heat generation from granitoid plutons.

Current research by YGS is focused on evaluating the geothermal potential along major crustal faults in southern Yukon. Activities are focused on the Denali, Teslin, and Tintina faults near the towns of Burwash Landing, Haines Junction, Teslin, and Watson Lake. Study areas are first evaluated using a series of geophysical methods, including magnetic, electromagnetic, magnetotelluric, gravity, and passive seismic surveys that are combined to produce 3D geological models across the fault structures (Figure 14). Data from these studies are used to determine locations of future temperature gradient wells (e.g., Witter, 2020; Tschirhart et al., 2022). Studies along the Denali fault are most advanced, with drilling to be completed in 2023. The objective is to install a long-term, down-hole monitoring site for temperature, stress, and seismicity along the active Denali fault zone. Analysis of LiDAR imagery is also being conducted to identify neotectonic features along the Denali fault, and petrophysical studies are in progress with the aim of modelling the regional hydraulic system in southwest Yukon. Finally, the YGS is completing a compilation of existing geothermal indicators, including previously unpublished studies commissioned by the Yukon Energy Corporation; this data will be made available through a web interface.

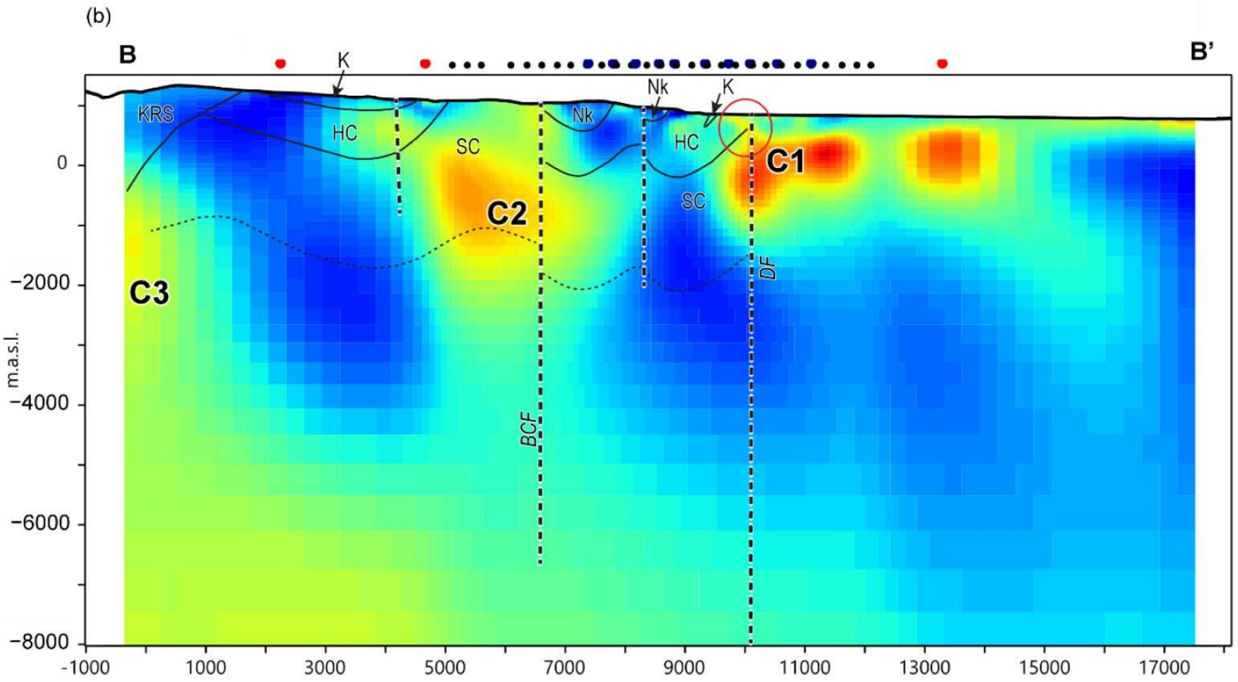

Figure 14. Yukon Geological Survey Research: Cross-section through 3D resistivity model for the Burwash Landing area, Yukon (after Tschirhart et al., 2022). Red circle shows location of conductor to be investigated by drilling of temperature gradient well.

The YGS geothermal research program is conducted in collaboration with communities and First Nation governments with funding from NRCan's ERPP and the Yukon government's *Our Clean Future* initiative. This work is being conducted in collaboration with researchers from the Geological Survey of Canada, United States Geological Survey, and Canadian universities.

2.9 Northwest Territories

The Government of Northwest Territories (GNWT) has developed several strategies to reduce greenhouse gas (GHG) emissions in the Northwest Territories (NWT), reduce the reliance on fossil fuels for its energy needs, increase energy security and affordability, and enhance sustainable energy development. Although a large portion of the Territory's electricity needs is supplied by hydroelectricity, diesel and gas are still main components of electricity generation in remote and isolated grids; hydrocarbons are also the main source of building heating. Geothermal energy is identified as one potential solution to satisfy future energy demands in the Territory.

The southeastern region of the NWT has been recognized to have elevated geothermal gradients (e.g. Grasby et al., 2013), and has been the focus of renewed research interest by the Northwest Territories Geological Survey (NTGS) and NRCan. Currently several concurrent research projects with different foci are underway to characterize the region's geothermal energy potential. As well, a research project investigating the geothermal energy potential of the Con Mine in the city of Yellowknife has recently been completed.

Fort Liard

Researchers at CanmetENERGY are currently investigating a hybrid and integrated system for the Indigenous off-grid community of Fort Liard (FL), NWT (Figure 1 and Figure 15), which is situated above a region of the Western Canada Sedimentary Basin (WCSB) that has excellent geothermal potential (Dehghani-Sanij and Wigston, 2022; Majorowicz and Grasby, 2021).

CanmetENERGY is in the process of completing a techno-economic feasibility assessment using HOMER and COMFAR software to determine the optimal design and operation of a hybrid system that can reliably meet the community's energy needs at the lowest cost and with the fewest environmental impacts. Preliminary modelling of a stand-alone geothermal system (with diesel used only as a backup during periods of maintenance) shows that the cost of energy (COE) is around 18 ¢/kWh, considering a lifespan of 30 years. The COE for the existing diesel-based system is 70.16 ¢/kWh (NTPC 2022). Ongoing work involves integrating wind power, solar power, and energy storage systems to determine if these result in a lower COE and even greater environmental benefits (e.g., reduced CO_2 emissions).

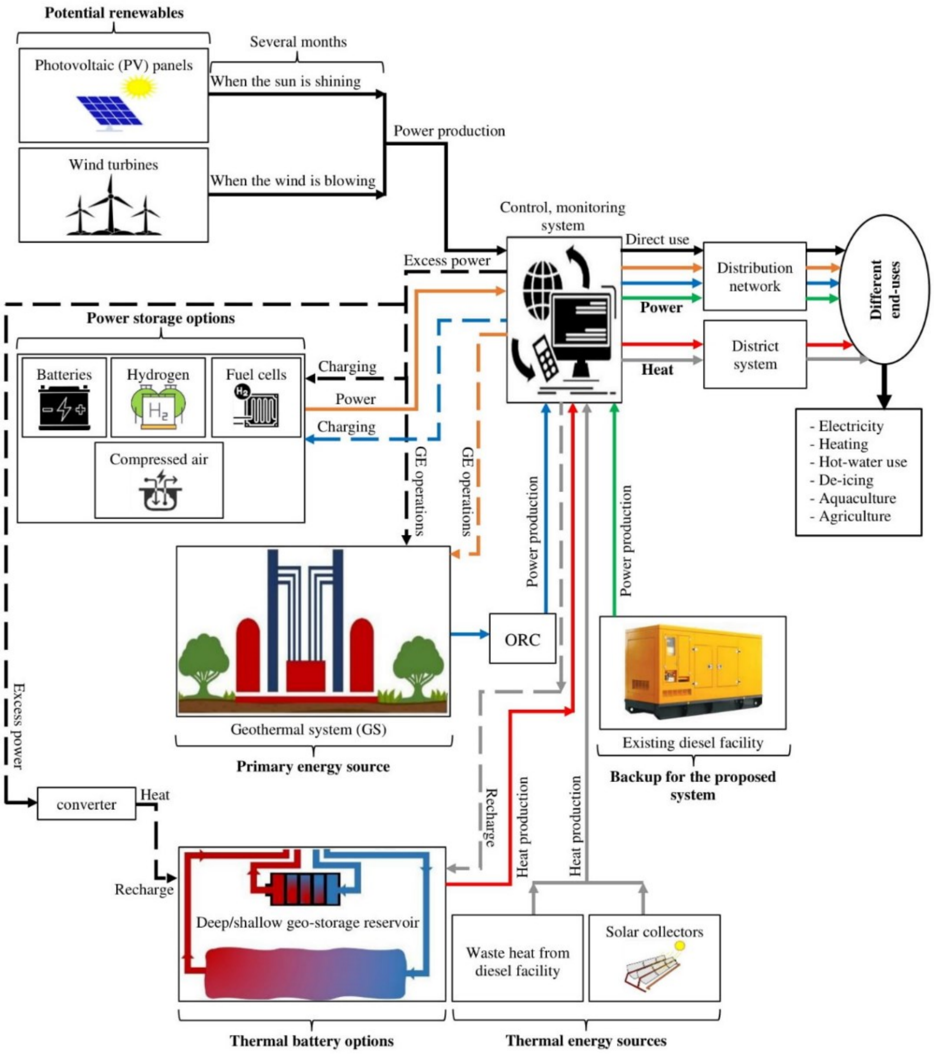

Figure 15. Fort Liard: A proposed hybrid and integrated geothermal system for Fort Liard, NWT (Dehghani-Sanij and Wigston, 2021).

NTGS: Liard Basin Geothermal Reservoir Characterization

The Liard Basin project (Figure 1), led by the NTGS, aims to gather baseline geologic data and fill knowledge gaps relating to reservoir quality of the prospective deep and hot geothermal reservoir rocks of the Nahanni Formation limestone and its regionally extensive dolomitized Manetoe Facies. The project was initiated in 2019 in collaboration with the Department of Infrastructure – Energy Division (INF-Energy). For this study, eight cores and nine field sites from the region were sampled in 2019 and 2021 respectively (Figure 16). The samples were analysed for porosity and permeability (routine core analysis), XRD mineralogy, SEM pore-space characterization, and thin-section petrography. In 2022, the NTGS entered into a collaborative partnership with researchers from INRS, who are in the process of compiling and interpreting the analytical data. The results of the study will be combined with legacy core analysis data from well files, and the study will expand to include other prospective formations. Preliminary results indicate that reservoir quality is limited through most of the strata, which comprise fine-grained and well-cemented limestone and crystalline dolomite (in the order of 0.01-0.1 mD and <<1 % porosity). Reservoir quality is, however, moderate locally through the stratigraphy, where dolomitization has increased vuggy pore space (1 to ~40 mD and 1-7 % porosity). Field observations support the observation of a patchy facies fabric. Additionally, the discontinuous nature of the Manetoe facies was noted in the field; in the southern part of the study area it is thick, well developed and laterally continuous, however toward the north it becomes increasingly discontinuous and only affects the limestone of the Nahanni Formation in discrete, several m to Dm wide lenses.

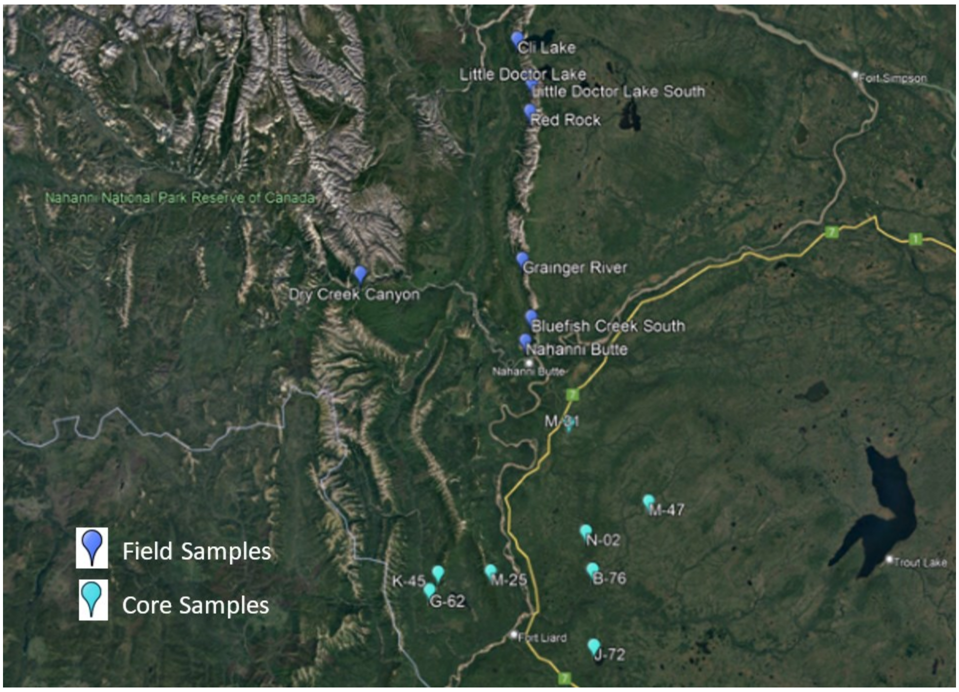

Figure 16. Liard Basin Geothermal Reservoir Characterization: Field and core sampling locations in the Ft. Liard area of the NWT.

NTGS: South Slave Geothermal Potential

This collaborative project between the NTGS and INRS aims to evaluate the geothermal resources in the South Slave region of the Northwest Territories (Figure 1). The objective of this study is to characterize thermohydraulic properties to better estimate temperature at depth and evaluate potential geothermal systems to be installed, aiming to better inform future decision making regarding clean and reliable local geothermal heat for the communities of Kakisa, Fort Providence, Hay River and Enterprise. The first phase of the project comprises measurement of the thermophysical properties of the main lithologic formations of the study area with the objective to identify potential targets for further exploration. A total of eighty-four samples were collected from forty-three wells that cover eight formations (Figure 17). Preliminary results show that the average thermal conductivity of the rock samples is between 2.8 $Wm\text{-}^{1}K^{-1}$ and 5.6 $Wm^{-1}K^{-1}$. The thermal diffusivity varies between $1.1x10^{-6}$ m^2s^{-1} and $2.2x10^{-6}$ m^2s^{-1}, and the volumetric heat capacity is between 2.3 MJ m^{-3} K^{-1} and 3.6 MJ m^{-3} K^{-1}. Using a cut-off value of 3.5 W m^{-1} K^{-1}, the results indicate that the limestones of the Slave Point and Horn Plateau Formations and the shales of the Watt Mountain Formation would be intermediate between conductive and insulating rocks, whereas the remainder of the formations would act as heat conductors. In terms of volumetric heat capacity, the Keg River Formation dolostone and the Chinchaga Formation anhydrite would have the best heat storage potential, although there is some variability among the lithologies. Forthcoming results will include hydraulic properties, geochemical, and mineralogical analysis of the samples. The aim is to define thermofacies for the evaluation of the geothermal potential of the study area, that also considers the thickness and lithological heterogeneity of the strata.

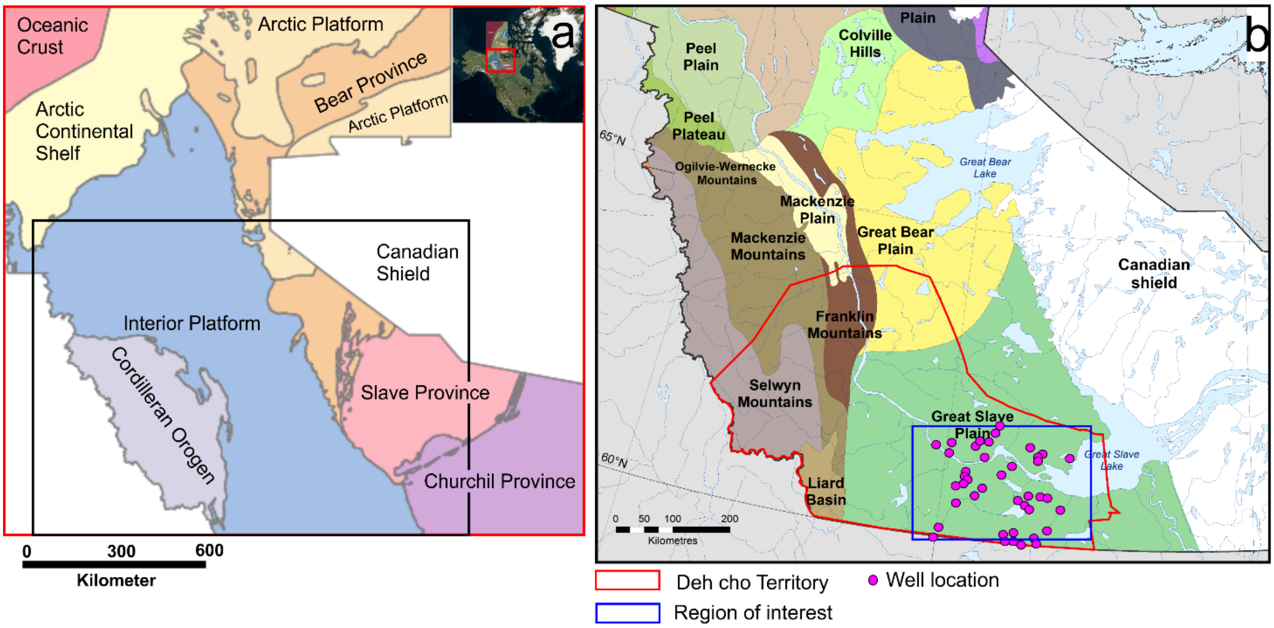

Figure 17. South Slave Geothermal Potential: Location of the 43 wells sampled for the South Slave geothermal study.

NTGS: Con Mine

In 2019-2021 the NTGS collaborated with the INRS and Geological Survey of Canada to model the geothermal energy potential of the flooded Con Mine in the city of Yellowknife (Figure 1). The Con Mine is an abandoned gold mine that operated from 1938 to 2003, and has a depth in excess of 1800 m. Data for this study consisted of water temperature measurements in mine shafts and one nearby borehole in order to obtain a reliable temperature gradient, regional fracture measurements along scan lines to determine hydraulic conductivity of the bedrock by Cubic's Law, and water quality assessment to determine scaling and corrosion potential. The results were used in analytical and numerical models to estimate the ultimate energy potential of the Con Mine geothermal system. This work showed that the Con Mine holds enough thermal energy to sustainably heat and cool buildings with a heat pump over 25 years. The energy delivered to the buildings can annually reach 2,510 MWh at a pump depth of 300 m for a flow rate of 0.06 m^3s^{-1}, while it increases to 3,770 MWh when the flow rate is 0.08 m^3s^{-1}. The thermal power extracted from the mine water during peak conditions is 562 kW and 843 kW in both cases. Installing the pump at a greater depth also allows to increase the thermal energy delivered to buildings which reaches up to 18,048 MWh for a pump located at 1 km depth, offering a heating capacity of 3.9 MW in peak conditions.

2.10 Nunavut

All communities in Nunavut rely on diesel. For this reason, Qulliq Energy Corporation (QEC), the energy utility company in Nunavut, has been interested in evaluating the territorial geothermal potential and in assessing some target communities for future geothermal development. The Phase I of the Nunavut geothermal feasibility study estimated that the technical power generation potential could between 59 MWe and 64 GWe in the Canadian Shield and between 662 MWe and 96 GWe in the sedimentary basins in the Arctic Islands (Minnick et al., 2018). However, important data gaps make this assessment uncertain, and additional data collection with drillings at target communities (e.g., Resolute Bay, Baker Lake; Figure 1) is necessary to properly define the resource potential (Minnick et al., 2018).

3. ACADEMIC RESEARCH

3.1 Geothermal Research and Programs at Canadian Universities

Several Canadian universities are active with geothermal programs and research, development, and innovation (RD&I) projects. Many of these programs are funded in part by Canadian federal grants through the National Science and Engineering Council of Canada (NSERC) in addition to university, provincial and territorial support. Beyond those listed below (Table 1), several other Canadian universities offer undergraduate and/or graduate programs with options to pursue research within the field of sustainable energy which includes work related to geothermal energy.

Table 1. Summary of Canadian universities with active geothermal R&D projects.

University	Geothermal research program
University of Alberta	→ Multi-disciplinary research for geothermal energy involving specialists working in geophysics, geology, geochemistry, mechanical engineering, risk management, safety and the built environment, energy law, and energy policy. → Geothermal and alternative energy: • Imaging, characterizing and modelling Canada's geothermal resources • Fluid/rock interactions in Canada's geothermal systems

	• Optimizing geothermal energy, production and utilizations technology • Socio-economic roadmaps to commercial geothermal energy production in Western Canada • More Information Here
University of Calgary	→ GeoS (Energi Simulation Centre for Geothermal Systems Research): • Multi-disciplinary research spanning development cycle of geothermal energy: from exploration geology to facilities to regulation and social acceptance • Thermal and fluid flows in reservoirs • Drilling, well designs and completions • Thermodynamics and energy conversions • Sustainability, social license, and Indigenous perspectives • Geothermal policy and law • More Information Here
Institut national de la recherche scientifique (INRS)	→ Geothermal program: • Northern geothermal potential research chair • Aquifers: a natural infrastructure for energy-efficient cooling to fight the urban heat island • Geothermal resources and technologies for active and closed mines • Analysis of heat transfer processes in favorable geothermal environments • Geothermal potential of sedimentary basins • Geothermal heat pump systems to heat greenhouses • Underground energy storage: heat, compressed air and hydrogen → Laboratoire ouvert de géothermie (LOG) – open access laboratory → Master in Earth Sciences – Joint program with INRS and Reykjavik University • Earth Science Master program with focus on renewables • More Information Here
Polytechnique Montreal	→ Geothermal program: • Thermal response test interpretation • Rapid and accurate simulation of ground coupled heat pump systems • Operation of standing column wells • More Information Here → Geothermal Research Chair: • Integration of standing column well in commercial an institutional building • More Information Here → Low temperature geothermal: • Graduate course that mixes notions of hydrogeology and geothermal • More Information Here
Concordia University	→ Sustainable Energy and Infrastructure Systems Engineering (SEISE) Lab: • Techno- economic feasibility analysis of geothermal systems • Environmental risk/impact assessment of borehole thermal energy storage (BTES) • Integration of geothermal energy into district heating systems • Reliability engineering for geothermal energy facilities management • Modeling, simulation, and optimization of hybrid renewable energy systems at building, district, and community scales • More Information Here
University of Waterloo	→ Waterloo Institute for Sustainable Energy (WISE): • Tools for analyzing power flow of modern microgrids at various scales • Compressed air offers energy storage insights using steel cased wellbores or geostorage • Solutions for greener energy and potable water – distillation and compressed air storage • Integrating local community knowledge into transitions from fossil fuel to renewable energy systems • Geothermal energy systems for remote, isolated communities • Low grade heat scavenging, storage and utilization for power and district heating • New technology for massively reduced CO2 oil sands exploitation • Deep liquid and solid waste injection and energy harvesting • More Information Here
University of Saskatchewan	→ Geothermal Research in the Department of Civil, Geological, and Environmental Engineering • Geothermal energy, groundwater modeling, heat transport in porous media, hydrogeology, geochemistry • More Information Here
University of Regina	→ Petroleum Technology Research Centre (PTRC) announced funding for University of Regina research project evaluating geothermal heat and integration of different energy sources at a proposed greenhouse facility in Estevan • Joint initiative between the University of Regina, PTRC (a research agency that aims to make all forms of sub-surface energy more efficient and environmentally sound which receives funding from Innovation Saskatchewan: a government agency that fosters innovation, research, and development of technology across Saskatchewan), Evolution

	Growers (a First Nations' owned startup working to improve food security and support for produce in Southern Saskatchewan), and Mitacs (a Canadian not-for-profit organization committed to funding partnerships between academic and industrial institutions to support innovation and job opportunities for students and postdocs). • More Information Here

3.2 University of Calgary

The University of Calgary Energi Simulation Centre for Geothermal Systems Research (GeoS) is a multi-disciplinary collaboration between students and researchers in the Departments of Chemical and Petroleum Engineering, Mechanical Engineering, Civil Engineering, Department of Geosciences, Faculty of Education, and the Faculty of Law. GeoS is working with industry partners and provincial and federal funding agencies for research opportunities for undergraduate, graduate, and post-graduate students in support of the Energi Simulation Centre's vision of "geothermal anywhere through improved exploration, drilling efficiency, well layouts, reservoir management, surface facilities, energy conservation, heat re-use, and close collaboration and buy-in from the community".

3.2 University of Alberta

Geothermal research at the University of Alberta began in the 1970s and 1980s with a focus on the WCSB (Jones & Majorowicz, 1987; Majorowicz & Jessop, 1981) This research declined in the following two decades, as federal research funding was largely suspended. Geothermal research began again from 2010-2015 with the Helmholtz – Alberta Initiative. This initially focused on investigating the role that geothermal heat could play in providing heat for the oilsands industry (Majorowicz et al., 2012) . It later diversified into quantifying other geothermal resources in the WCSB and surrounding areas (Gray et al., 2012; Weides & Majorowicz, 2014; Figure 7). Since 2016, geothermal research has diversified with support from Alberta Innovates and the Future Energy Systems program at the University of Alberta, funded by the Canada First Research Excellence Fund with matching and in-kind support from provincial and local municipal agencies and several industry partners. Cumulatively, the research program has received more than $7.5 million in funding through 2023. Research within the program is divided into the following areas.

Western Canada Sedimentary Basin

The University of Alberta has continued to investigate the geothermal potential of the WCSB using data from the oil and gas industry to map hot sedimentary aquifers (Banks & Harris, 2018). A new, state-of-the-art fluid/rock interaction laboratory has been established at the University of Alberta. Related studies have explored a number of the practical aspects of developing low-enthalpy geothermal resources in a sedimentary basin environment. This has included studies of Stirling engines for geothermal applications. Stirling engines are externally heated, closed-cycle heat engines capable of running with temperature differences of just a few degrees centigrade and convert heat energy into electricity. Geothermal applications of Stirling engines in locations such as the WCSB are challenging because fluid temperatures are less than 150 °C. Progress is summarized by Stumpf (2019); Michaud (2020); Nicol-Seto (2021); Hasanovich & Nobes (2021); and Lottmann et al., (2021). Eghbali et al., (2021) modelled heat extraction from a WCSB type geothermal reservoir using a multi-component, multi-phase model.

Applications of direct heat use has included heating cattle feed water (Schiffner et al., 2022) and heating water for processing oilsands to extract bitumen (Hu et al., 2022). The role that repurposed deep oil wells could play in geothermal development in the WCSB, including the performance of deep borehole heat exchangers has also been investigated (Akbarpoor & Zhong, 2022; Dincoglu et al., 2022; Hu et al., 2020; Hu et al., 2021).

Partnership in the commercial Tu Deh-Kah project at Fort Nelson began with construction of reservoir and simple flow models (Renaud et al., 2021) and is now developing funding for integrated geophysical, geological, and engineering studies. Socio-economic studies of how geothermal development can economically benefit the community are also in progress. A reservoir study was also undertaken at South Swan Hills oil field to delineate favorable zones in the reservoir for long-term hot water production (Noyahr, 2022).

Canadian Cordillera

Several fault-hosted and volcano-hosted geothermal resources have been identified in the Canadian Cordillera in British Columbia and the Yukon. The University of Alberta has been working with both commercial developers and government agencies to better define these resources. Some research has taken a regional scale approach, seeking to identify factors that control the distribution of resources. Hanneson and Unsworth (2023a) developed a regional scale resistivity model from an array of magnetotelluric soundings in the southern Canadian Cordillera and investigated the spatial relationship between thermal springs and mid-crustal fluid content. Finley et al. (2022) investigated the state-of-stress on major fault systems in the southeastern Canadian Cordillera to determine which faults might have elevated permeability and act as conduits to transport high temperature fluids from depth to the surface. Other studies have focused on specific geothermal resources located on major fault systems. Areas studied include Valemount (Lee, 2020), the M'Deek geothermal area near Terrace (Vestrum & Unsworth, 2022) and Watson Lake. Finally, the University of Alberta has contributed to studies of the high temperature geothermal resources in the Garibaldi Volcanic Belt. Research has been focused on defining the deeper parts of the hydrothermal and magmatic system beneath the Mount Meager geothermal prospect. Fieldwork took place in 2019-2021 and the resulting data used to generate a 3-D resistivity model (Grasby et al., 2020; Hanneson & Unsworth, 2023b). This project is now focused on Mount Cayley where a similar approach is being used to determine the location and size of the heat source beneath this volcano.

Northern Canada

This region of Canada is currently dependent on diesel and other hydrocarbons for both heat and electricity generation. This is associated with high shipping costs and also contributes to a number of environmental challenges. In collaboration with the Nunavut government and other university researchers, a program is under development to evaluate how geothermal energy could contribute to heat generation and electricity production. The research focus to date has been on novel approaches to geophysical imaging of the upper 1-2 km of the subsurface, to understand both the thermal conditions and groundwater characteristics.

Socio-Economic Studies

Additional research has focused on the socio-economic factors involved with bringing geothermal power to remote, northern communities. Research has focused on assisting communities looking to diversify and decarbonize energy sources, repurpose their hydrocarbon infrastructure, and finance reclamation liabilities, with geothermal power for heat and electricity. Jurisdictional reviews of regulations and royalties in mature economies help Canadian authorities determine the best ways to promote geothermal energy production through regulation, networking, incentives, and other resourcing. By examining the economics, researchers also help mediate negotiated settlements between municipalities and geothermal energy developers. This process provides an opportunity for longitudinal studies on how to best support communities' adoption of renewable technologies. Examples of these studies include the results of Percy, (2022), Schiffner et al. (2022), and Nadkarni et al. (2022).

3.4 Institut national de la recherche scientifique

The Centre Eau Terre Environnement of the Institut national de la recherche scientifique based in Quebec City developed a geothermal research program over the past eight years with the goal of improving the understanding of heat transfer mechanisms impacting the performance of geothermal energy systems. Such knowledge can help to reduce installation costs and develop competitive geothermal technologies. Furthermore, a core laboratory to characterize thermal and hydraulic properties of geological materials, named LOG (*Laboratoire Ouvert de Géothermie*), was put in place with major funding from the Canadian Foundation for Innovation and has been operated in an open-source fashion. Additionally, a research chair supported by the *Institut nordique du Québec* to study the northern geothermal potential was awarded to INRS.

Research within INRS geothermal group has been focused on improving thermal response tests (TRTs), on improving methods to characterize in-situ thermal properties (e.g., oscillatory TRT), and on finding new approaches to estimate terrestrial heat flux. The group has also been active in untapping the geothermal potential of the St. Lawrence Lowlands, Anticosti Island, Magdalen Islands, Kuujjuaq, Nevado del Ruiz in Colombia, Madagascar and Djibouti.

3.5 Polytechnique Montreal

A NSERC Industrial Chair in geothermal energy for geothermal standing column wells in industrial buildings is active in the Department of Civil, Geological and Mining Engineering of Polytechnique Montreal. This Geothermal Research Chair aims to rapidly remove the barriers to the use of permanent column wells (PCP) in institutional buildings and thus reduce their heating and cooling costs, the demand for electrical power from the network and the greenhouse gas emissions resulting from the use of fossil fuels. The numerous research activities of the Chair are based on three demonstration projects carried out in schools over a five-year period. The objectives of the research activities and demonstration projects are to 1) reduce peak power demand and operate PCPs efficiently, 2) acquire, design, validate and demonstrate the potential of PCPs, 3) monitor groundwater quality in the vicinity of PCPs, and 4) train, change perceptions, disseminate and transfer knowledge.

3.6 Geological Survey of Canada

The Geological Survey of Canada has undertaken geothermal research in Canada since the 1970's, including some of the first research defining geothermal potential across the country. Recently several projects have been operating integrated with other provincial and territorial research organizations as well as academia. Early research in the 1980's defined the highest temperature geothermal resources known in the country (over 250 °C), in the Garibaldi Volcanic Belt of BC. Ongoing research has focused on reducing the exploration risk in these volcanic systems by developing new tools to predict the occurrence of permeability at depth.

A second focus has been northern communities that are largely off grid and rely on imported hydrocarbons for heat and electricity. These can be offset by local geothermal resources. However, subsurface geothermal resources are difficult to identify, even more so in northern Canada were thermal data are limited, and regions of thick permafrost can hide thermal anomalies. To address these challenges this project is developing new geophysical, geochemical, and remote sensing techniques to identify 'blind' geothermal resources. This project closely ties to geothermal research activities in Yukon and NWT. Part of the work examines potential of abandoned mines that are often flooded, which then make then a large reservoir that can have water production at extremely high volume, work led by INRS.

Hot sedimentary basins have been another focus, mostly in the Western Canada Sedimentary Basin and its sub-basins. Activities include regional studies of heat potential as well as focused research on specific abandoned or end of life petroleum fields. In addition, long term planning and design is being considered for Tight unconventional gas (TUG) formations contain additional energy (such as geothermal, compressed gas and abandoned gas flow) at the end of production. Their economic values may surpass natural gas itself and most remain untapped. An innovative solution of making proper use of the untapped resource and existing wellbores could double the energy value as compared with the outcome of production from the TUG or the geothermal energy resources alone, such helping accelerate the low carbon transition. The feasibility of converting active and abandoned oil and gas wells to CO_2 geological storage site and geothermal energy producer is also being examined. Converting these oil and gas wells for CO_2 storage and geothermal energy producer can store more CO_2 in geological formations and reduce CO_2 emission to atmosphere, while generates renewable energy to offset the field operation needs. In addition, the conversion could significantly reduce the cost of well cleanup and reclamation, and extend the life of existing field infrastructure and employs out-of-work petroleum sector workers, and diversifies the economic portfolio of petroleum-dominated oil and gas provinces.

Additional work is being conducted that examines the potential for EGS development in basement rocks underlying sedimentary basins, in particular the nature of water rock interaction and how this can affect permeability of the fracture dominated systems.

Lower temperature sedimentary basins are also being examined for their potential for heat production, specifically in the Bécancour area, Quebec. This project has two components: 1) a modeling study that investigates the use of geothermal heat for building heating, which explores the use of deep borehole heat exchangers (DBHEs, installed in new boreholes or in re-purposed oil and gas wells) and doublets; and 2) a combined lab and modeling study that uses 3D pore network images from CT-scans (medical and micro) to simulate fluid flow and heat transfer.

The GSC is also undertaking conceptual modelling studies of closed loop systems, including horizontal and inclined systems to assess the thermodynamic feasibility of these concepts. Results showed that closed loop systems are viable but only in rock types with sufficient thermal conductivity.

CONCLUSIONS

The pursuit of geothermal energy in Canada has been highly dependent on external factors such as strength of the economy, prevalence of other energy industries, and interest in developing renewable energies. As such, development of the industry has started and halted several times since the 1970s. However, interest has renewed over the last decade which is evident in the involvement of provincial and federal governments, increased research, and new projects across the country. Provincial governments of Alberta and Quebec recently developed geothermal framework act for the provinces, while British Columbia and Nova Scotia have had acts in place for many years. Yukon and Northwest Territories have not created frameworks specifically for geothermal development, but have released plans to develop more renewable resources. Several provincial governments and the federal government have also provided grants and supported research.

Many new geothermal projects have progressed across several provinces, including British Columbia, Alberta, Saskatchewan, Quebec, and Nova Scotia. Research and analyses have been conducted in the territories of the Yukon, Northwest Territories, and Nunavut with hopes to diversify their energy sources. There are several universities across Canada with strong geothermal research programs. The research is highly variable, covering a wide range of topics such as deep geothermal resources, ground source heat pumps, energy engineering, direct heat use, and many more.

Progress of the geothermal industry in Canada has been significant in recent years. With many projects in development and extensive research being conducted, many Canadians hope to see completion of geothermal projects and a greater understanding of the resources.

REFERENCES

Akbarpoor, A.M., and Zhong, L.: A comprehensive review of the application of solar assisted ground source heat pump (SAGSHP) systems in Canada. *Canadian Society for Mechanical Engineering International Congress*, (2022).

Allan Gray, D., Majorowicz, J., and Unsworth, M.J.: Investigation of the geothermal state of sedimentary basins using oil industry thermal data: case study from Northern Alberta exhibiting the need to systematically remove biased data, *Journal of Geophysics and Engineering*, **9**(5), (2012), 534–548.

Banks, J., and Harris, N.B.: Geothermal potential of Foreland Basins: A case study from the Western Canadian Sedimentary Basin, *Geothermics*, **76,** (2018), 74–92.

Bédard, K., Comeau, F.-A., Millet, E., Raymond, J., Malo, M., and Gloaguen, E.: Évaluation des ressources géothermiques du bassin des Basses-Terres du Saint-Laurent (No. 1659), Institut national de la recherche scientifique - Centre Eau Terre Environnement, Québec, (2016).

Bédard, K., Comeau, F.-A., Raymond, J., Gloaguen, E., Malo, M., and Richard, M.-A.: Deep geothermal resource assessment of the St. Lawrence Lowlands sedimentary basin (Québec) based on 3D regional geological modelling, *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, **6**, (2020), 46.

Bédard, K., Comeau, F.-A., Raymond, J., Gloaguen, E., Malo, M., Richard, M.-A.: Deep geothermal resource assessment of the St. Lawrence Lowlands sedimentary basin (Québec) based on 3D regional geological modelling, Geomechanics and Geophysics for Geo-Energy and Geo-Resources, **6**, (2020), 46.

Bédard, K., Comeau, F.-A., Raymond, J., Malo, M., and Nasr, M.: Geothermal Characterization of the St. Lawrence Lowlands Sedimentary Basin, Québec, Canada, *Natural Resources Research*, **27**, (2017), 479–502.

Borealis GeoPower Inc.: Nova Scotia geothermal investigation proposal, (2022), 12 p.

Colpron, M.: Potential radiogenic heat production from granitoid plutons in Yukon: Yukon Geological Survey, Open File, 2019-16 (2019).

Comeau, F.-A., Séjourné, S., and Raymond, J.: Assessment of geothermal resources in onshore Nova Scotia. Institut national de la recherche scientifique - Centre Eau Terre Environnement, Québec, (2020), 216 p.

Dehghani-Sanij, A.R., Wigston, A.: Feasibility assessment of hybrid geothermal systems in remote northern Canadian communities, CanmetENERGY-Ottawa, NRCan, Ottawa, ON, Canada, (2022) (in progress).

Dincoglu, Y., Akbarpoor, A.M., and Zhong, L. Evaluate the application of ground-source heat pumps under freezing soil conditions in Alberta, *Canadian Society for Mechanical Engineering International Congress*, (2022).

Eghbali, S., Banks, J., and Nobes, D.S.: A numerical study on compositional modeling of two-phase fluid flow and heat transfer in vertical wells, *Journal of Petroleum Science and Engineering*, **201**, (2021), 108400.

Fairbank, B.D., and Faulkner, R.L.: Geothermal Resource of British Columbia, Geological Survey of Canada Open File 2526 (1992)

Friend, M. and Colpron, M.: Potential radiogenic heat production from Cretaceous and younger granitoid plutons in southern Yukon: Yukon Geological Survey, Open File, 2017-60, 1:1000000, (2017).

Gascuel, V., Bédard, K., Comeau, F.-A., Raymond, J., and Malo, M.: Geothermal resource assessment of remote sedimentary basins with sparse data: lessons learned from Anticosti Island, Canada, *Geothermal Energy*, **8**, (2020), 3.

Gascuel, V., Pasquier, L.-C., Raymond, J., and Hénault-Ethier, L.: Mémoire de l'INRS – Projet de Loi 21 – Pour l'amélioration de la loi pour mettre fin á la recherche et á la production d'hydrocarbures en soutenant la mise en valeur durable des réservoirs souterrains. Institut national de la recherche scientifique. Déposé dans le cadre des consultations de la CAPERN au sujet du projet de loi 21 « Loi visant principalement à mettre fin à la recherche et à la production d'hydrocarbures ainsi qu'au financement public de ces activités », (2022), 30 p.

Gascuel, V., Raymond, J., Rivard, C., Marcil, J.-S., and Comeau, F.-A.: Design and optimization of deep coaxial borehole heat exchangers for cold sedimentary basins, *Geothermics*, **105**, (2022), 102504.

Geotherma Solutions Inc.: Thermal response test and assessment of the shallow geothermal potential at the Kuujjuaq Forum, Nunavik, Québec. Geotherma Solutions Inc, (2022), 33 p.

Giordano, N., and Raymond, J.: Field report and monitoring plan of the ground source heat pump system for the community swimming pool in Kuujjuaq (Nunavik, Canada). Rapport de recherche R2007. Institut national de la recherche scientifique - Centre Eau Terre Environnement, Québec, (2020).

Giordano, N., Lamarche, L., and Raymond, J.: Evaluation of Subsurface Heat Capacity through Oscillatory Thermal Response Tests, *Energies, 14,* (2021), 5791.

GNWT. 2018a. 2030 Energy Strategy. Government of the Northwest Territories. Available: https://www.inf.gov.nt.ca/en/services/energy/2030-energy-strategy

GNWT. 2018b. 2030 NWT Climate Change Strategic Frameword. Government of the Northwest Territories. Available: https://www.enr.gov.nt.ca/en/services/climate-change/2030-nwt-climate-change-strategic-framework

Grasby, S. E., Ansari, S.M., Bryant, R., Calahorrano-Di Patre, A., Chen, Z., Craven, J. A., Dettmer, J., Gilbert, H., Hanneson, C., Harris, M., Hormozzade, F., Liu, J., Montezadian, D., Muhammad, M., Russell, J.K., Salvage, R.O., Savard, G., Su, H., Tschirhart, V., Williamson, A.R.: *The Garibaldi Volcanic Belt geothermal energy project - Mount Meager 2019 field program*, (2020).

Gunawan, E., Giordano, N., Jensson, P., Newson, J., Raymond, J.: Alternative heating systems for northern remote communities: Techno-economic analysis of ground-coupled heat pumps in Kuujjuaq, Nunavik, Canada, Renewable Energy **147**, (2020),1540–1553.

Hanneson, C., and Unsworth, M.J.: Magnetotelluric imaging of the magmatic and geothermal systems beneath Mount Meager, southwestern Canada. *Canadian Journal of Earth Sciences Special Issue: Canadian Cordilleran Volcanism. In Review.* (2023a).

Hanneson, C., and Unsworth, M.J.: Regional-scale resistivity structure of the middle and lower crust and uppermost mantle beneath the southeastern Canadian Cordillera and insights into its causes. *Geophysical Journal International. In Review,* (2023b).

Hasanovich, L., and Nobes, D.: Investigation of effect of heat exchanger size on power output in low-temperature difference Stirling engines, *E3S Web of Conferences*, **313**, (2021), 03002.

Hassan Aden, A., Raymond, J., Giroux, B., Sanjuan, B.: New Insights into Hydrothermal Fluid Circulation Affected by Regional Groundwater Flow in the Asal Rift, Republic of Djibouti. Energies, **14**, (2021), 1166.

Hassan Aden, A., Raymond, J., Giroux, B.: Numerical Modeling of Hydrothermal System Circulation Beneath Asal Rift, Republic of Djibouti, Energies **15**, (2022), 9310.

Hickson, C.J., Proenza, Y., Huttrer, G., Yehia, R., Majorowicz, J., Lund, J., Boyd, T., Woodsworth, G., Kunkel, T., Moore, M. and Hjorth, L. (Tuya Terra Geo Corp. and Geothermal Management Company Inc).: Direct Use Geothermal Resources in British Columbia, Section A Summary of Findings. Geoscience BC, Report 2016-07, 189 p http://www.geosciencebc.com/s/2015-022.asp and http://www.geosciencebc.com/s/Report2016-07.asp

Hickson, C.J., Kumataka, M., Akto, P., Cotterill, P., Benoit, D., Eccles, R., Colombina, M., and S. Collins: Alberta No1: The province's first electrical geothermal project, Proceedings World Geothermal Congress, Reykjavik, Iceland, (May 2021)

Hickson, C., Hubbard, B., Smejkal, E.: Geothermal in Alberta – The importance of creating a regulatory environment conducive to supporting the growth of a geothermal industry, GeoConvention, Calgary, Alberta, (June 20-22, 2022a)

Hickson, C., Hubbard, B., Smejkal, E.: Geothermal in NWT – Regulatory Considerations, Yellowknife Geoscience Forum (November 2022b)

Hickson, C.J., Smejkal, E., Rathbone, J.: Geoexchange to Deep Conventional Geothermal Energy Extraction Technology Comparison, GeoConvention, Calgary, Alberta, (June 20-22, 2022c)

Hickson, C. J., Raymond, J., Dusseault, M., Fraser, T., Huang, K., Marcia, K., Miranda, M., Poux, B., Fiess, K., Ferguson, G., Dale, J., Banks, J., Unsworth, M., Brunskill, B., Grasby, s., and Witter, J.:Geothermal Energy in Canada – Times Are "a Changing", In Geothermal Resources Council, Transactions, **44**, 2020, Reno, Nevada, (October 18-21, 2020)

Holroyd, Peggy, and Jennifer Dagg. 2011. "Building a regulatory framework for geothermal energy development in the NWT."51. Available: https://www.enr.gov.nt.ca/sites/enr/files/building_a_regulatory_framework_for_geothermal_in_the_nwt.pdf

Hu, X., Banks, J., Guo, Y., and Liu, W.V.: Utilizing geothermal energy from enhanced geothermal systems as a heat source for oil sands separation: A numerical evaluation, *Energy*, **238**, (2022), 121676.

Hu, X., Banks, J., Guo, Y., Huang, G., and Liu, W.V.: Effects of temperature-dependent property variations on the output capacity prediction of a deep coaxial borehole heat exchanger, *Renewable Energy*, **165,** (2021), 334–349.

Hu, X., Banks, J., Wu, L., and Liu, W.V.: Numerical modeling of a coaxial borehole heat exchanger to exploit geothermal energy from abandoned petroleum wells in Hinton, Alberta, *Renewable Energy*, **148**, (2020), 1110–1123.

Huang, K., Champollion, Y., and Hickson, C.: Preliminary Results and New Insights from a Deep Temperature Log in the Western Canada Sedimentary Basin, *Proceedings,* GRC Transactions, **45**, (2021), 12.

Jessop, A.: Geothermal energy from old mines at Springhill, Nova Scotia, Canada, *Proceedings*, World Geothermal Congress 1995:1, (1995), 463-468.

Jones, F. W., and Majorowicz, J.A.: Regional trends in radiogenic heat generation in the Precambrian basement of the Western Canadian Basin, *Geophysical Research Letters*, **14**(3), (1987), 268–271.

Kerr Wood Leidal: An Assessment of the Economic Viability of Selected Geothermal Resources in British Columbia Geoscience BC Report 2015-11, (2015) https://cdn.geosciencebc.com/project_data/GBCReport2015-11/GBC2015-11_KWL_Geothermal%20Economics_Project_Report_27Sep16.pdf

Koubikana Pambou, C.H., Raymond, J., Miranda, M.M., and Giordano, N.: Estimation of In Situ Heat Capacity and Thermal Diffusivity from Undisturbed Ground Temperature Profile Measured in Ground Heat Exchangers, *Geosciences,* **12**, (2022), 180.

Langevin, H., Giordano, N., Raymond, J., and Gosselin, L.: Oscillatory thermal response test using heating cables: A novel method for in situ thermal property analysis, *International Journal of Heat and Mass Transfer*, **202**, (2023), 123646.

Lee, B.M.: *Improving Exploration for Geothermal Resources with the Magnetotelluric Method* [Doctor of Philosophy, University of Alberta], (2020).

Li, C.-F., Lu, Y. and Wang, J.: A global reference model of Curie-point depths based on EMAG2, *Scientific Reports*, **7**, (2017), 45129.

Lottmann, M., de Rouyan, Z., Hasanovich, L., Middleton, S., Nicol-Seto, M., Speer, C., and Nobes, D. Development of a 100-Watt-Scale Beta-Type Low Temperature Difference Stirling Engine Prototype, *E3S Web of Conferences*, **313,** (2021), 08004.

Majorowicz, J. and Grasby, S.E.: Deep Geothermal Heating Potential for the Communities of the Western Canadian Sedimentary Basin, *Energies*, **14**, (2021), 706.

Majorowicz, J., Unsworth, M., Chacko, T., Gray, A., Heaman, L., Potter, D.K., Schmitt, D.R., and Babadagli, T.: Geothermal Energy as a Source of Heat for Oil Sands Processing in Northern Alberta, Canada. In *Heavy-oil and Oil-sand Petroleum Systems in Alberta and Beyond*. American Association of Petroleum Geologists, (2012).

Majorowicz, J.A., and Jessop, A.M.: Regional heat flow patterns in the Western Canadian Sedimentary Basin, *Tectonophysics*, **74**(3–4), (1981), 209–238.

Malone, L.: Direct use of geothermal heat in Nova Scotia, Dunsky, Montreal, (2021), 99 p.

Michaud, J.: *Low Temperature Difference Alpha-Type Stirling Engine for the Experimental Determination of Optimal Parameters to Maximize Shaft Power* [Master of Science, University of Alberta], (2020).

Miranda, M., M., Raymond, J., Willis-Richards, J., and Dezayes, C.: Are Engineered Geothermal Energy Systems a Viable Solution for Arctic Off-Grid Communities? A Techno-Economic Study. *Water, 13,* (2021), 3526.

Miranda, M.M., and Raymond, J.: Assessing Kuujjuaq's (Nunavik, Canada) deep geothermal energy potential. Rapport de recherche R2109., Institut national de la recherche scientifique - Centre Eau Terre Environnement, Québec, (2022), 122 p.

Miranda, M.M., Raymond, J., and Dezayes, C.: Uncertainty and Risk Evaluation of Deep Geothermal Energy Source for Heat Production and Electricity Generation in Remote Northern Regions. *Energies,* **13**, (2020), 4221.

Miranda, M.M., Velez Márquez, M.I., Raymond, J., Dezayes, C.: A numerical approach to infer terrestrial heat flux from shallow temperature profiles in remote northern regions, Geothermics, **93**, (2021), 102064.

Moreno, D., Lopez-Sanchez, J., Blessent, D., Raymond, J.: Fault characterization and heat-transfer modeling to the Northwest of Nevado del Ruiz Volcano, Journal of South American Earth Sciences, **88**, (2018), 50–63.

Nadkarni, K., Lefsrud, L.M., Schiffner, D., and Banks, J.: Converting oil wells to geothermal resources: Roadmaps and roadblocks for energy transformation, *Energy Policy*, **161**, (2022), 112705.

Nasr, M., Raymond, J., and Malo, M.: Évaluation en laboratoire des caractéristiques thermiques du bassin sédimentaire des Basses-Terres du Saint-Laurent, *Proceedings,* 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference, Québec City, Canada (2015).

Nicol-Seto, M.E.: *Investigation of a Drive Mechanism Modification to Increase Thermodynamic Power of a Low Temperature Differential Gamma Type Stirling Engine* [Master of Science, University of Alberta], (2021).

Nova Scotia: Geothermal Energy - Current Activity, (2022), available at: https://energy.novascotia.ca/renewables/geothermal-energy/current-activity (accessed November 24, 2022).

Noyahr, C.: v. *Geothermal Reservoir Characterization of the South Swan Hills Oil Pool, Swan Hills, Alberta* [Master of Science, University of Alberta], (2022).

NTPC, Here's how we supply power in your community, Northwest Territories Power Corporation (NTPC), Hay River, NTW, Canada, 2022. Retrieved from https://www.ntpc.com/your-community/community-map (Accessed 14 June 2022)

Percy, D.: Richard Riegert Memorial Lecture: Ownership Issues in the Production of Geothermal Energy, *Alberta Law Review*, (2022), 523.

Rajaobelison, M., Raymond, J., Malo, M., Dezayes, C., Larmagnat, S.: Assessment of Petrophysical Rock Properties in North Madagascar: Implications for Geothermal Resource Exploration. Natural Resources Research, 30, (2021), 3261–3287.

Rajaobelison, M., Raymond, J., Malo, M., Dezayes, C., Larmagnat, S.: Understanding heat transfer along extensional faults: The case of the Ambilobe and Ambanja geothermal systems of Madagascar, Geothermics, 104, (**2022**), 102455.

Rajaobelison, M., Raymond, J., Malo, M., Dezayes, C.: Classification of geothermal systems in Madagascar, Geothermal Energy **8**, (2020), 22.

Raymond, J., Langevin, H., Comeau, F.-A., and Malo, M.: Temperature dependence of rock salt thermal conductivity: Implications for geothermal exploration, *Renewable Energy*, **184**, (2022), 26 -35.

Renaud, E., Weissenberger, J.A. W., Harris, N.B., Banks, J., and Wilson, B.: A reservoir model for geothermal energy production from the Middle Devonian Slave Point Formation, *Marine and Petroleum Geology*, **129**, (2021), 105100.

Richard, M.-A., Giroux, B., Gosselin, L., Kendall, J., Malo, M., Mathieu-Potvin, F., Minea, V., and Raymond, J.: Intégration de la géothermie profonde dans le portefeuille énergétique canadien. IREQ-2017-0032. Hydro-Quebec, Quebec, (2016), 185 p.

SaltWire: Concept design for Springhill Geothermal Business Park underway, (2019), available at: https://www.saltwire.com/atlantic-canada/federal-election/concept-design-for-springhill-geothermal-business-park-underway-336905/ (accessed November 25, 2022).

Schiffner, D., Banks, J., Rabbani, A., Lefsrud, L., and Adamowicz, W.: Techno-economic assessment for heating cattle feed water with low-temperature geothermal energy: A case study from central Alberta, Canada, *Renewable Energy*, **198**, (2022), 1105–1120.

Stumpf, C.: *Parameter Optimization of a Low Temperature Difference Gamma-Type Stirling Engine to Maximize Shaft Power* [Master of Science, University of Alberta], (2019).

Tschirhart, V., Colpron, M., Craven, J., Hormozzade Galati, F., Enkin, R.J. and Grasby, S.E.: Geothermal exploration in the Burwash Landing region, Canada, using three-dimensional inversion of passive electromagnetic data, *Remote Sensing*, **14**, (2022), p. 5963.

Vélez Márquez, M.I., Raymond, J., Blessent, D., and Philippe, M.: Terrestrial heat flow evaluation from thermal response tests combined with temperature profiling, *Physics and Chemistry of the Earth, Parts A/B/C,* **113**, (2019), 22–30.

Vélez Márquez, M.I., Raymond, J., Blessent, D., Philippe, M., Simon, N., Bour, O., and Lamarche, L.: Distributed Thermal Response Tests Using a Heating Cable and Fiber Optic Temperature Sensing, *Energies, **11,*** (2018), 3059.

Vélez, M.I., Blessent, D., Córdoba, S., López-Sánchez, J., Raymond, J., Parra-Palacio, E.: Geothermal potential assessment of the Nevado del Ruiz volcano based on rock thermal conductivity measurements and numerical modeling of heat transfer, Journal of South American Earth Sciences **81**, (2018), 153–164.

Vestrum, Z., and Unsworth, M.J.: Integrated Electrical and Electromagnetic Exploration at the M'Deek Geothermal Field, *AGU Fall Meeting*, (2022).

Weides, S., and Majorowicz, J.: Implications of Spatial Variability in Heat Flow for Geothermal Resource Evaluation in Large Foreland Basins: The Case of the Western Canada Sedimentary Basin. *Energies*, **7**(4), (2014), 2573–2594.

Witter, J.B and Miller, C.: Curie point depth mapping in Yukon: Yukon Geological Survey, Open File 2017-3, (2017), 37 p.).

Witter, J.B., Miller, C.A., Friend, M. and Colpron, M.: Curie point depths and heat production in Yukon, Canada, *Proceedings*, 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, CA, USA (2018).

Witter, J.B.: Early-stage exploration for geothermal energy resources along the Denali fault near Duke River, Yukon: Yukon Geological Survey, 2020-3, (2020), 62 p.).