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Geothermal Energy in Canada – Kickstarting an Industry

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ABSTRACT

Geothermal research and exploration in Canada have a long and rich past with many prominent and important early researchers, explorers and developers who worked within Canada and abroad. Geothermal Canada was launched in 1973 as the Canadian Geothermal Association and has been dedicated since that time to supporting the geothermal community in Canada. Now after more than 40 years along, the geothermal landscape is finally beginning to change, and it is important to review the current and recent projects, research, and initiatives. Vibrant research groups exist throughout universities across the country; 464 scientific publications on geothermal energy written by Canadian researchers are reported in Scopus from 2014 to 2018. The focus is on resource assessment, direct-use and adapting technology for remote communities located in arctic to subarctic climatic zones. Provincial governments in British Columbia, Alberta, Saskatchewan, and Quebec are supporting projects along with the exchange of ideas. In Canada's north, including the Yukon, Nunavut, Nunavik and the Northwest Territories, there are initiatives to assess the geothermal potential, especially through engineered geothermal systems (EGS), and to support research for development challenges in extreme environments. Canada's federal government, through Natural Resources Canada, awarded a 25.6 million dollars grant to the Deep Earth Energy Corp. project in Saskatchewan, and in Alberta a 25.4-million-dollar contribution grant was awarded to the Alberta No. 1 geothermal project. Additionally, the Geological Survey of Canada continues to support geothermal research. As the global landscape continues to evolve away from hydrocarbons for heating and electricity generation, Canada is well-placed to fill in the gap with thermal and electrical generation from sedimentary basins, deep fault, and volcanic systems, as well as to be a leader in EGS. Canadian scientists and engineers are poised to make significant contributions both here in Canada and globally.

1. INTRODUCTION

Located in the higher latitudes of the northern hemisphere, Canada has very high heating loads and is prime for geothermal development, in particular, direct use. Much of the Canadian landmass experiences arctic to subarctic climatic conditions with areas of continuous permafrost and high heating loads that exceed 7000 degree-days[1]. With a mean annual temperature of 1 °C, Canada is ripe for large-scale geothermal development (Figure 1). This significant heating requirement, coupled with a transitioning of the hydrocarbon economy and a need to reduce greenhouse gases, has been a driver for Canada's new developing geothermal projects, research, government funding, and framework development.

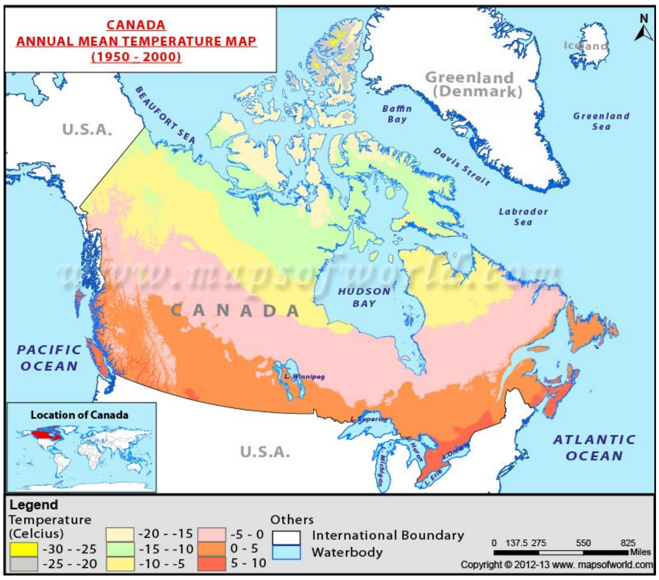

Figure 1: Canada's mean annual temperature is approximately 1 °C (Maps of World 2012).

[1] Degree days is a unit used to determine the heating requirements of buildings, representing a fall of one degree below a specified average outdoor temperature (usually 18°C or 65°F) for one day. The higher the number of degree days, the greater the heating requirement.

Canada is already a leader in geoexchange (shallow heat pumps) deployment but has lagged in deep geothermal direct-use and power generation. Interestingly, geothermal has a long history in Canada. The late 1960s and into the 1970s was a time when many nations (including Canada) felt that they faced substantial petroleum shortages as well as rising prices. This growing concern became a crisis in 1973 when the Organization of Arab Petroleum Exporting Countries (OAPEC), declared an embargo on nations supporting Israel and the Yom Kippur War. This was further exacerbated in 1979 in the wake of the Iranian revolution. The impact on oil prices can be seen in Figure 2, spurring geothermal exploration worldwide as governments looked for alternatives to hydrocarbons.

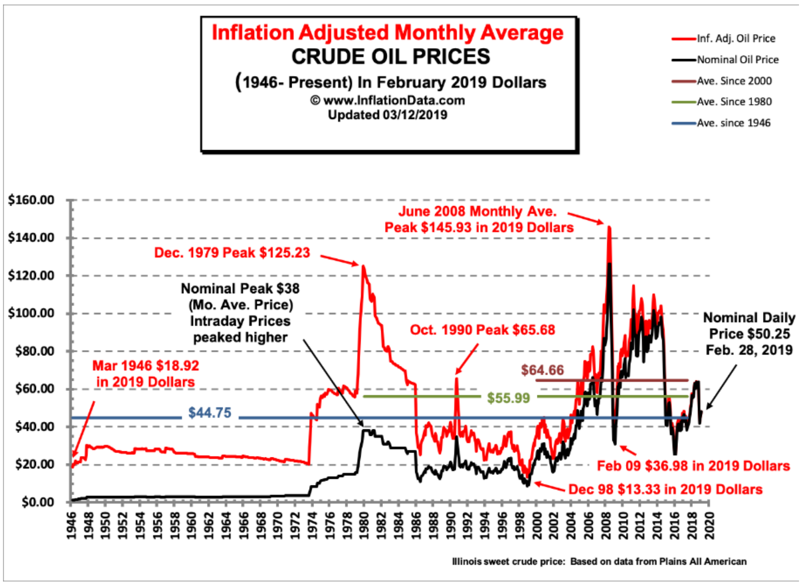

Figure 2: Inflation adjusted monthly crude oil price averages from 1946 to March 12, 2019 in February 2019 US dollars (Inflation Data (2019)).

A second wave of exploration occurred in the mid- to late 2000s when skyrocketing prices for gas and oil suggested that the value proposition for geothermally generated electricity and heat was becoming more positive. According to Inflation Data (2019) the major peaks in oil price occurred in December 1979 at $125.23, October 1990 at $65.68, and June 2008 at $145.93 (all inflation adjusted to 2019 US dollars). These increasing prices spawned exploration waves and many new companies were created worldwide, including in Canada. However, with decreasing hydrocarbon prices, coupled with the financial crisis of 2008, many companies disappeared or could no longer move projects forward.

Project risk and the need for geothermal companies to fund projects with equity in early project development phases left many companies insolvent post-2010. Unlike other renewable energy projects (wind and solar in particular), early project debt financing is generally unavailable to geothermal projects. Additionally, many projects were being developed in jurisdictions not eligible for funding from such bodies as the World Bank or other regional lending institutions (e.g., Interamerican or African Development Banks). Many of the publicly listed companies in the mid-2000s boom were small companies listed on the Toronto Stock Exchange (TSX) or TSX-Venture Exchange. Although these companies, some of whom were based in Canada, managed to raise millions of dollars, coffers were soon empty as the reality of high project development costs, the challenges of setting up subsidiaries in foreign jurisdictions, and falling power purchase agreement prices began to impact their value proposition and ability to raise additional capital.

In Canada, the negative financial backdrop of the past ten years has been coupled with the availability of low-cost electricity generated by natural gas and hydro electric power. In June 2019, Geothermal Canada president published a general letter to members (Hickson 2019) as well as presented government officials and other political parties with a two-page summary of information about geothermal energy. In these documents it was pointed out that, despite global studies on the cost of geothermal energy shown to be cost competitive in the global marketplace (see, for example, LAZARD 2018), geothermal had seen minimal movement in the Canadian marketplace. Wind and solar have been at the forefront of renewables, but neither can provide a base load, dispatchable power and infrastructure longevity (on the order of decades) that geothermal energy does.

In Canada, the perception of high costs and the fact that less than 2% of Canada's landmass has access to high quality geothermal fluids that can be pumped at high rates (>90 °C, >100 L/s) (Figure 3). Sedimentary basins, and in particularly the Western Canada Sedimentary Basin (WCSB), are massive hydrocarbon resources and are heavily extracted. According to Natural Resources Canada (NRCan) in 2019, Canada's energy sector directly employed more than 269,000 people and indirectly supported over 550,500 jobs; the energy sector accounts for over 11% of nominal Gross Domestic Product (GDP); government revenues from energy were $14.1 billion in 2017 and more than $799 million was spent on energy research, development, and deployment by governments in 2017-18. Additionally, Canada is the sixth largest energy producer, the fifth largest net exporter, and the eighth largest consumer of energy globally. These facts, along with the unknown impacts of geothermal production alongside hydrocarbons, make geothermal a hard sell in Canada. However, with all that said, Canada is uniquely positioned to take advantage of its own geothermal resources as well as export its knowledge and technology for drilling, pumping, handling massive quantities of hot water, and development in extreme climates, globally.

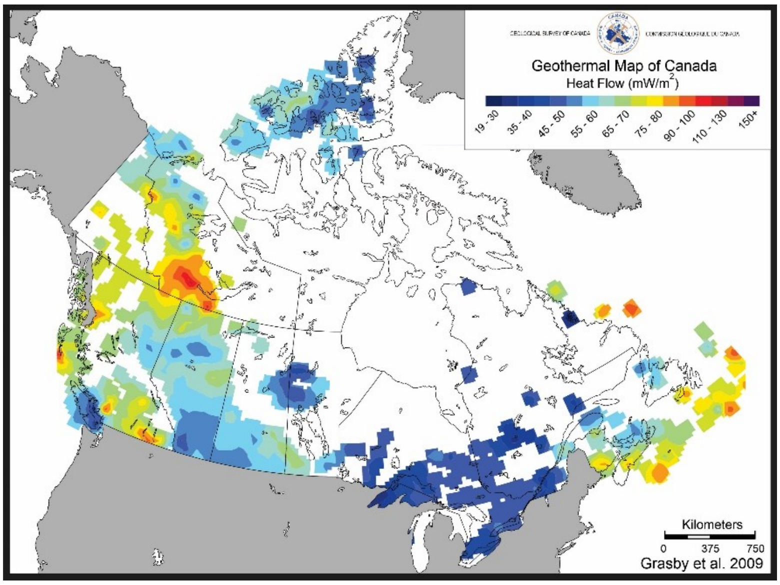

Figure 3: Geothermal map of Canada (Grasby et al. 2009). White areas represent no data, but in central and eastern Canada characterize areas underlain by metamorphic and granitic rocks of the Canadian Shield.

As the realities of climate change become apparent to nations and the need for stronger action is being voiced by the populace, geothermal is seeing renewed interest. As a base load energy source, particularly for space heating, the value of geothermal is being recognized. Roadmaps recently published by the Netherlands (Master Plan 2018) and the European Technology and Innovation Platform on Deep Geothermal (2018) clearly enunciate the role geothermal can play in the reduction of greenhouse gases. Additionally, the realities of supply-chain assurance for heat energy needs has led governments to adopt policies to transition away from gas as a fuel source. In Canada, with continued abundance of gas for heating and power generation, the value proposition is more on preservation of the hydrocarbons for purposes for which they are ideally suited (petrochemicals, fuels, etc.). Proving that commercial geothermal fluid production can co-exist alongside petroleum extraction will be confirmed as projects are developed and begin production of power and thermal energy.

The Government of Canada and many of the provinces and territories are heeding the voices of the populace and making commitments in the field of renewable energy. Governments have stepped up funding geothermal research, development, and innovation (RD&I) over the past three years. In the western basins where the sediments are deep enough and hot enough for power generation, two projects have been funded (Alberta No. 1 in Alberta and Deep Earth Energy (DEEP) Corp. in Saskatchewan) through NRCan's Emerging Renewable Power Program (ERPP). Although these projects are small in terms of proposed electrical power output, they are the test beds for expansion and were awarded from a pool of renewable projects where no extra value was awarded to geothermal projects for base load or heat generation.

Figure 4: Researcher from INRS investigates physical rock properties of typical Canadian Shield rocks near Kuujjuaq, Nunavik, Quebec.

However, Canada is a vast country and although high quality resources are found in some parts of Canada (Figure 3), more than 90% of the landmass underlain by crystalline rocks is unsuitable for conventional geothermal development. It is these crystalline rocks that make up what is termed geologically the "Canadian Shield" (Figures 1 and 4) and that offer a significant RD&I challenge for Canadian geothermal projects. Combined with very high heat load requirements over much of this region (Figure 1) there is clear impetus for Canadians to invest in engineered geothermal systems (EGS) and cold environment adaptations for geothermal technology. Even subsurface waters a few tens of degrees above zero, present a very significant temperature difference (ΔT) that can be usefully used for heat energy. Developing this technology, along with supporting traditional projects to help the energy transition, is the challenge for governments across Canada.

This paper outlines some of the progress and work done in Canada and abroad by Canadians and Canadian companies and organizations in pursuit of geothermal energy generation – both for electricity and heat.

2. CANADIAN GEOTHERMAL ASSOCIATION AND GEOTHERMAL CANADA

Geothermal research and geothermal exploration in Canada both have a long and rich past with many prominent and important early researchers, explorers and developers who worked within Canada and abroad. The energy crisis of the 1970s spawned development in many countries and prompted the Canadian Federal Government, along with Provincial partners, to invest in geothermal research. To support this work, the Canadian Geothermal Association (CGA) was launched in 1973 at the inaugural meeting of the US-based Geothermal Resources Council (GRC) meeting in Brawley, CA. The association was formalized in 1974. In 2018 the Society was rebranded Geothermal Canada. The association counts among its members many of the leading researchers, developers, and explorers in Canada. Three of these early pioneers were honoured by Geothermal Canada in 2018 with honourary life memberships — Allan Jessop, Tim Sadlier-Brown, and Andy Nevin, who have played key roles in the development of geothermal projects in Canada. The current executive is Steve Grasby, President (president@geothermalcanada.org), Catherine Hickson Vice-president, (vicepresident@geothermalcanada.org), Jeff Witter, Treasurer (jeff@innovategeothermal.com) and Katie Huang, Secretary (admin@geothermalcanada.org,).

The association is officially registered in British Columbia as the *Pan Canadian Society for Geothermal Research, Innovation, & Collaboration,* colloquially known as Geothermal Canada (GC). The Society is a not-for-profit organization formulated under the *Societies Act* of British Columbia #20068829 and was later registered in Alberta with the same status and name. GC is dedicated to supporting the geothermal community in Canada to assist with networking to promote the exchange of ideas and innovations in all aspects of the geothermal world. The Society supports workshops, conferences, and other forms of information exchange such as dissemination about the industry in Canada internationally. It has recently accepted the role of creating a National Geothermal Roadmap under the leadership of Natural Resources Canada.

Updates to its members and the geothermal community are provided via membership and its webpage (http/www.geothermalcanada.org). Membership is encouraged and helps the association maintain a digital presence as well supporting Canadian geothermal research and development. Board members are volunteers and many of our corporate members help fund events and the work of the association in order to keep membership fees low and accessible in the interest of networking and information sharing. Help us carry out our mission by joining.

3. ACADEMIC RESEARCH AND EDUCATION INITIATIVES

3.1 Geothermal Research and Study Programs at Canadian Universities (contributed by Mafalda Miranda (mfldmiranda@gmail.com))

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. Among these, Table 1 highlights the research carried out by *Institut national de la recherche scientifique* in partnership with Université Laval and École de Technologie Supérieure, the Geothermics Research Group of the University of Alberta, the University of Manitoba, the Vancouver Island University, and the Concordia University. Beyond these universities, several others offer undergraduate and/or graduate programs with options to pursue research within the geothermal energy field (Table 2).

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

University	Programs and research projects
Institut National de la Recherche Scientifique (INRS)	Geothermal research program • Aquifers: a natural infrastructure for energy-efficient cooling to fight the urban heat island • Northern geothermal potential research chair • Geothermal resources and technologies for active and closed mines • Analysis of heat transfer processes in favorable geothermal environments • The Grenville Province of southern Quebec: geophysical interpretations and implications for deep geothermal and regional correlations
University of Alberta	Geothermal Research Group: • Imaging, characterizing, and modelling Canada’s geothermal resources • Fluid/rock interactions in Canada’s geothermal systems • Optimizing geothermal energy production and utilization technology • Socio-economic roadmaps to commercial geothermal energy production in Western Canada

University of Manitoba	Groundwater Engineering program: • Geothermal behaviour of the @Source-Energy Pipe System • University of Manitoba Efficient and Renewable Technology Hub (UMEARTH)
Vancouver Island University	Nanaimo campus • District Geo-Exchange Energy System—Phase I
Concordia University	Sustainable Energy and Infrastructure Systems Engineering (SEISE) lab: • Identification of the technical and economic feasibility of geothermal systems in northern Québec region
Université du Québec à Montréal	GEOTOP – Research Centre on the Dynamics of the Earth System
McGill University	Trottier Institute for Sustainability in Engineering and Design
University of Windsor	Turbulence and Energy Laboratory
University of Waterloo	Waterloo Institute for Sustainable Energy: • Tools for analyzing power flow of modern microgrids • Compressed air calculations offer energy storage insights • Solutions for greener energy and potable water • Integrating local community knowledge into transitions from fossil fuel to renewable energy systems
Simon Fraser University	Groundwater Resources Research Group (GRRG)
University of British Columbia	Clean Energy Research Centre
Polytechnique Montréal	The Trottier Energy Institute

Table 2: Examples of Canadian universities actively offering geothermal courses and geothermal research options

University	Undergraduate program	Graduate program
University of Guelph		M.Eng. Program • Mechanical Engineering
Saint Mary's University	B.Sc. Program • Environmental Science • Geology	
Université Laval		PhD Program • Mechanical Engineering • Earth Sciences
Carleton University	B.Eng. Program • Sustainable and Renewable Energy Engineering	
Queen's University	B.Eng. Program • Geological Sciences and Geological Engineering	
University of Windsor		M.Eng. Program • Environmental Engineering
University of Regina		M.Sc. Program • Geology
University of Victoria		M.Sc. • Earth and Ocean Sciences
University of Calgary	B.Sc. Program	

	• Natural Sciences – Energy Sciences Concentration	
Polytechnique Montréal		M.Eng. Program • Civil, Geological and Mining Engineering
École de Technologie Supérieure		M.Eng. and M.A.Sc. Program • Master of Renewable Energies and Energy Efficiency
Institut national de la recherche scientifique		M.Sc. bidiplomation program • Earth Sciences (INRS) • Renewable Energy (Reykjavik University)

3.2 Review of Canadian Scientific Publications Made During the Last 5 Years (contributed by Jasmin Raymond (jasmin.raymond@inrs.ca)**)**

A Scopus search with ''geothermal'' in keywords, title and abstract revealed that 11,872 documents have been published in this field over the past five years, from the beginning of 2014 until the end of 2018. Publications were sorted according to country affiliation of authors. Canada is ranked seven, with 464 publications, after the six countries with most contributions to the geothermal literature over the past five years, namely the United States of America (2,498), China (2,055), Germany (999), Italy (775), United Kingdom (571) and Japan (498). Hence, the Canadian contribution to geothermal science remains outstanding, given that the population of Canada is smaller than all of the above countries, and that geothermal power is not yet produced in Canada, although geothermal direct use is widespread with utilization of geothermal heat pumps from coast to coast.

The Ontario Tech University, University of Alberta, University of Calgary, University of British Columbia, McGill University, *Polytechnique de Montréal*, *École de Technologie Supérieure*, *Institut national de la recherche scientifique*, Natural Resources Canada and *Université Laval* are the top ten institutions that published geothermal studies (Figure 5). Broad subject categories of interest to the Canadian geothermal literature are earth and planetary sciences with 29% of publications, followed by energy (26%), engineering (16%), environmental science (13%) and other fields (16%) including agricultural and biological sciences, physics, chemistry, mathematics, and computer science, just to name a few.

The publications released by authors with Canadian affiliations that attracted the most interest were evaluated with the number of citations cumulated until July 2019 for each year of publication in the three major subject categories mentioned above. Topics of the papers with high impact concern geothermal heat pump systems, high to low temperature geothermal power plants, geological setting associated to both shallow and deep geothermal resources, renewable and sustainable energy solutions in which geothermal is an important component, as well as integration of geothermal energy in the oil and gas sector. A non-exhaustive review limited to peer reviewed articles in scientific journals is given to identify important research trends.

In terms of important research trends in the earth and planetary sciences category, the work of Dehkordi and Schincariol (2014; 30 citations) on the performance of closed-loop ground heat exchangers impacted by groundwater flow was highly cited. Crustal stress orientation with implications for deep geothermal systems (Reiter et al. 2014; 34 citations), hydrothermal degassing of magma chambers (Kennedy et al. 2016; 33 citations), prediction of ground surface temperature (Ouzzane et al. 2015; 29 citations) and heavy metals in hydrothermal systems (Tardani et al. 2017; 19 citations) were also topics of highly cited journal articles. Work conducted on a decision-making scheme for renewable power (Al Garni et al. 2016; 55 citations), hot water generation for oil sands processing from enhanced geothermal systems (Hofmann et al. 2014a and b; 53 citations) and energetic studies of multigenerational solar-geothermal systems (Al-Ali and Dincer 2014; 52 citations) were of most interest for articles in the energy subject category.

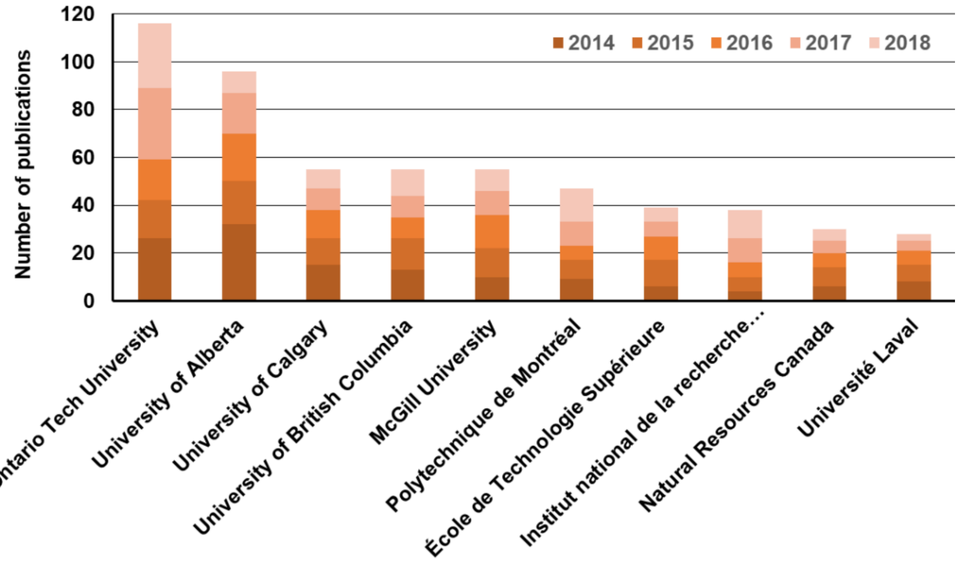

Figure 5: Number of geothermal publications released by the most active Canadian institutions in this field over the past five years.

Cited studies in the engineering category were related to the simulation of ground heat exchangers with a heat injection rate varying along segments of boreholes (Cimmino and Bernier 2014; 61 citations), methods to design geothermal heat pump systems based on cost minimization (Robert and Gosselin 2014; 37 citations) and abandoned petroleum wells as sustainable sources of geothermal energy (Templeton et al. 2014; 33 citations). Dincer and Acar (2015; 127 citations) further completed a study that rates geothermal as the most sustainable energy alternative for power generation when combining economic and environmental factors, such as land use, water contamination and waste issues. All these studies, contributing to a diversified Canadian geothermal literature, clearly show the importance and potential of geothermal energy, which is expected to increase its shares in the future Canadian energy budget to decrease greenhouse gas emissions and reduce the environmental impact of energy production.

3.3 *Institut National de la Recherche Scientifique* (INRS) (Contributed by Jasmin Raymond (jasmin.raymond@inrs.ca) and Mafalda Miranda (mfldmiranda@gmail.com))

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 five years. The objective of the research was to improve the understanding of heat transfer mechanisms that impact the performance of both shallow and deep geothermal system operations in order to reduce installation cost and develop competitive geothermal technologies. 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. A research chair supported by the *Institut nordique du Québec* to study the northern geothermal potential was additionally awarded to INRS.

At INRS, significant scientific developments were achieved in the field of thermal response tests to design geothermal heat pump systems (Koubikana Pambou et al. 2019; Raymond et al. 2014, 2015a, 2016; Raymond et al.2019; Raymond and Lamarche, 2014; Rouleau et al. 2016; Vélez Márquez et al. 2018), improving the field tests with alternative approaches using heating cables or temperature profiles to better characterize subsurface heterogeneities and the impact of groundwater flow. Work was also made to map the subsurface thermal conductivity distribution and put forward a new a thermostratigraphic concept helping to design geothermal heat pump systems (Raymond et al. 2017, 2019), or decrease the borehole thermal resistance of ground heat exchangers with alternative pipe configurations (Raymond et al. 2015b; Lamarche et al. 2018). This work is to better constrain the length of boreholes and potentially reduce system installation cost.

Sedimentary basins of eastern Canada, such as the St. Lawrence Lowlands, were studied to assess deep geothermal resources suitable for power generation with regional heat transfer models and geophysical well log analysis (Bédard et al. 2014, 2017; Nasr et al. 2018; Langevin et al. 2019; Gascuel et al. 2020). This work has revealed target anomalies with a geothermal gradient as high as 40°C km-1. Further studies were conducted to image reservoir properties such as macro porosity distribution with innovative X-ray scanning techniques of dry and saturated core samples (Larmagnat et al. 2019).

The potential development of geothermal heat pumps, thermal energy storage and deep enhanced (engineered) geothermal (EGS) systems in the cold climate of the Canadian Arctic is being studied. The region of focus is Nunavik (Belzile et al. 2017; Comeau et al. 2017; Giordano et al. 2018). Overburden and bedrock thermohydraulic properties near Kuujjuaq were assessed to conduct simulations (Figure 4). These studies show, despite the unbalanced heating loads and an energy demand above 8000 heating degree days below 18°C, that geothermal heat pump systems can be operated in such a subarctic climate. Thermal energy storage can provide space heating to reduce diesel consumption even though solar radiation varies seasonally (Giordano and Raymond 2019) and EGS may be a long-term option for heat and power (Miranda et al. 2018, 2020). Investigations were also conducted overseas to help developing countries such as Colombia with the assessment of their geothermal resources potential (Blessent et al. 2016; Vélez Márquez et al. 2015). This assessment provided critical numerical models to understand the impact of discrete fracture flow on the occurrence of hydrothermal manifestations (Moreno et al. 2018). All studies contributed to improving understanding of heat transfer mechanisms related to geothermal system performances. More than 3.5 M$ were obtained in funding at INRS from provincial and federal governments over the past five years to conduct geothermal research with a team of about 15 students and professionals, while a similar level of funding is expected for the upcoming years to continue the dynamic research program.

3.4 University of Saskatchewan (contributed by Grant Ferguson (grant.ferguson@usask.ca))

The University of Saskatchewan hydrogeology group has been involved in a series of projects related to geothermal energy. A focus of many of these projects has been to characterize the hydrogeologic properties of various formations within the Western Canada Sedimentary Basin. The permeability of the Cambrian/Ordovician Deadwood Formation and Winnipeg Formation, which are currently a target for the DEEP geothermal project, were characterized in a recent project. The Red River Formation, which may also have geothermal potential, was also characterized in a recent joint project with the Geological Survey of Canada. The permeabilities of various shallower strata have been characterized at a regional scale. Those formations could become important for direct-use projects or for disposal of brines from deeper geothermal energy projects.

In addition to the above-mentioned projects assessing hydrogeologic properties, regional scale assessments of fluid movement are underway as part of a Global Water Futures project. While there is enormous geothermal potential in sedimentary basins, widespread development will require coordination with the oil and gas industry, and consideration of induced seismicity, in addition to the overlying groundwater resources.

3.5 University of Alberta (contributed by Jonathan Banks (jbanks@ualberta.ca) and Martyn Unsworth (unsworth@ualberta.ca))

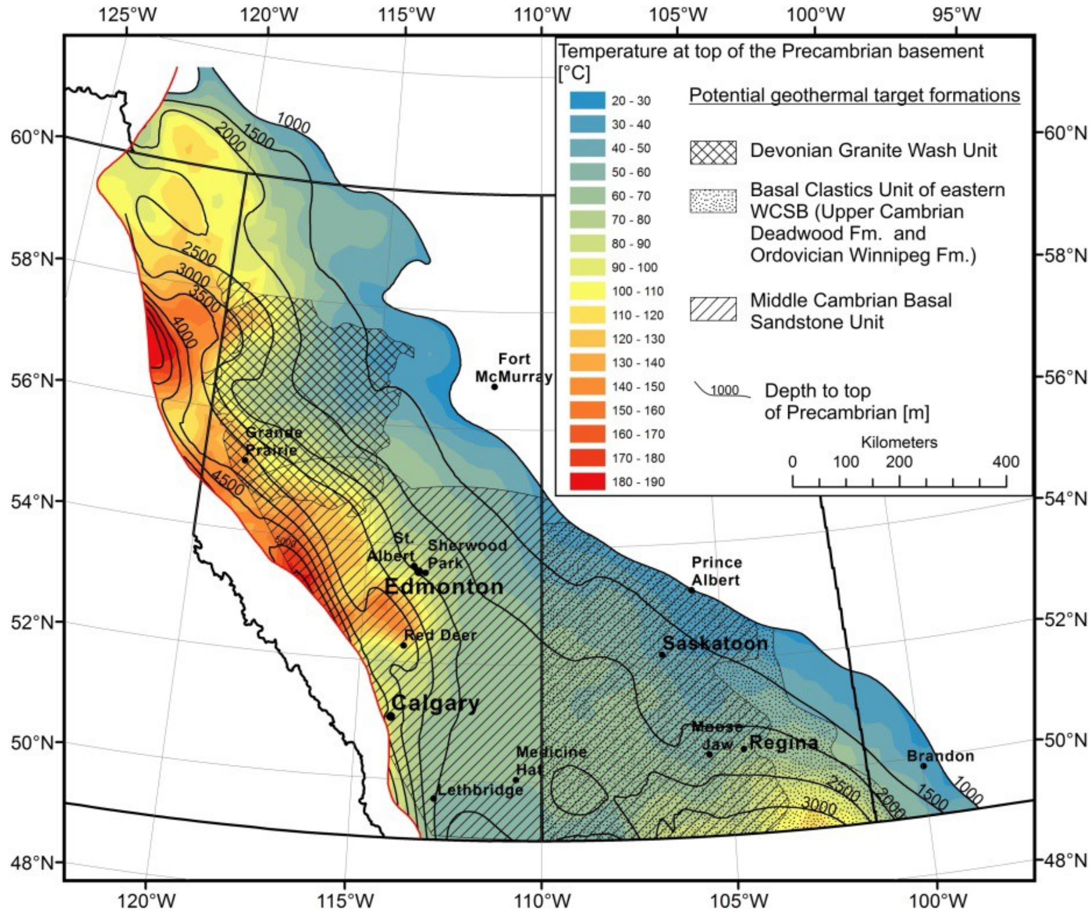

Figure 6: Temperature at the top of the Precambrian basement with potential geothermal target formations. The Precambrian basement is one of the key target zones for development in the WCSB (Figure 5 from Weides and Majorowicz 2014)

Pioneering work by University of Alberta (U of A) researcher Dr. Jacek Majorowicz has laid the foundation for the development of geothermal resources in the WCSB) as shown in Figure 6. His work and the work of colleagues over several decades is reflected in what we as Canadians know about heat flow in Canada (Figure 3; cf. Grasby et al. 2009; Gray et al. 2012; Jones and Majorowicz 1987; Jones et al. 1985; Majorowicz and Grasby 2010 and 2019; Majorowicz and Jessop 1981; Majorowicz and Moore 2014; Majorowicz et al. 1999). A 2014 publication (Weides and Majorowicz 2014) elegantly outlines the potential of the WCSB for geothermal development (Figure 7).

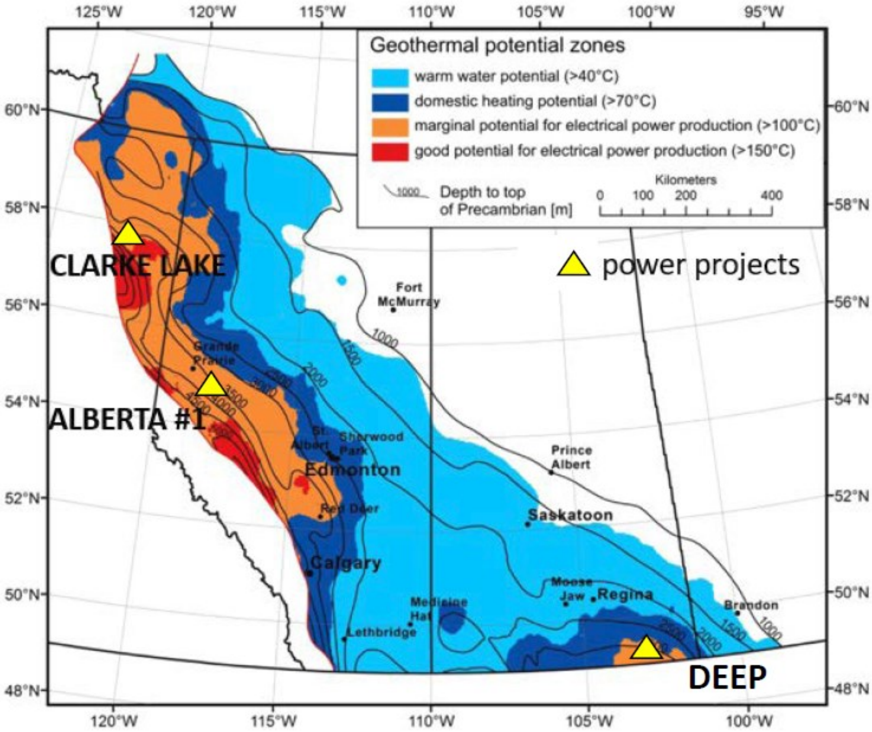

Figure 7: Possible geothermal applications based on the temperature at the top of the Precambrian basement. Also shown in as yellow triangles are three power development projects currently underway in the WCSB (adapted from Weides and Majorowicz 2014)

Building on the foundation of early work at the U of A, the past five years has seen the geothermal energy research program at the U of A evolve from a small group of individual researchers working independently from one another to a unified program spanning five university faculties. This research program is currently supported through the U of A's Future Energy Systems program (partly funded by the Canada First Research Excellence Fund), with matching and in-kind support from various provincial and local municipal agencies, as well as several industry partners. Cumulatively, the research program is supported with ~$7.5 million in funding through 2023. Research carried out in the program is led by ten co-principal investigators and currently employs about 30 students, post-doctoral fellows, and research associates. Research within the program is divided into 4 discrete projects.

The first project is focused on identifying and characterizing geothermal resources within the Canadian Cordillera, with target areas in the Rocky Mountain Trench (SE British Columbia), the Tintina Fault (central Yukon) and the Garibaldi Volcanic Belt (SW British Columbia). Research in this project uses a combination of non-invasive geophysics, traditional geological field work, and modern geochemical thermometry to map favourable areas for further research and development (cf. Palmer-Wilson et al. 2018a and 2018b).

The second project is focused on exploitation of geothermal resources within the Western Canadian Sedimentary Basin. Research in this project uses the abundance of data from the Canadian oil and gas industry to map hot sedimentary aquifers in the deep subsurface (cf. Banks and Harris 2018). The geothermal potential of these aquifers is determined using a combination of classic hydrocarbon reservoir characterization techniques, volumetric heat-in-place assessments, and reactive transport modeling. Within the context of this project, the University of Alberta has established a new, state-of-the-art fluid/rock interaction laboratory.

The aim of the third project is to develop novel uses of low-enthalpy geothermal resources. This project has two main areas. The first area involves the development of Stirling engines for geothermal applications. Stirling engines are externally heated, closed-cycle heat engines capable of running at 0.5ºC temperature differences. The prototype engines are designed to economically produce electrical power in the 60 to 90 ˚C temperature range. To facilitate the repurposing of the hundreds of thousands of deep wells in the Western Canadian Sedimentary Basin, the second area of this project is focused on the development of deep borehole heat exchangers and novel commercial uses for low-grade heat in cold climates.

To support these three projects, the fourth project focuses on the socio-economic factors involved with bringing geothermal power to communities. Research in this project focuses on assisting remote and northern communities, as well as communities looking to diversify their hydrocarbon economies, with geothermal power for heat and electricity. Jurisdictional reviews of regulations and royalties in mature geothermal economies are performed to help Canadian authorities determine the best ways to legislate geothermal energy production at home. The economics of geothermal energy production in Canada are studied. Researchers in this project also help mediate negotiated settlements between municipalities and geothermal energy developers. This process provides an opportunity for longitudinal studies on how communities adopt renewable technologies.

3.6 Waterloo (Contributed by Maurice Dusseault (mauriced@uwaterloo.ca)**)**

The University of Waterloo (UW) is pursuing the concept of smart hybrid integrated geothermal systems (SHIGS), with a focus on remote communities in Canada's north (north of where the mean annual temperature is -30 to -25°C; Figure 1). The department noted that high-grade geothermal is available under less than 2% of Canada's landmass, and that warm fluids at high rates (>90°C, >100 L/s) are generally only available in the western basins where the sediments are deep enough, therefore, UW decided to limit their geothermal research domain to the rest of Canada (90% of the land area), which includes areas underlain by strong, low-porosity igneous and sedimentary rocks (for example Toronto, Montréal, Halifax, Vancouver, Iqaluit, Yellowknife, and Winnipeg).

The SHIGS that the department is studying involve both shallow and deep aspects. The deep case arises when a reasonably large temperature difference (ΔT) is needed to generate power and supply heat, in some proportion. For example, if temperatures of 60°C can be accessed at depth or in a thermal repository, organic Rankine Cycle (ORC) engines can provide some power for lights and appliances. The shallow geothermal aspect is the implementation of a ground source heat pump and heat repository system so that heat can be stored and used seasonally. To the knowledge of the researchers, this integration is a novel direction, and they are trying to work out all the energy issues (energy production, rates, storage, recovery, etc.). The hybrid aspect is the same as for a hybrid (EV) car: storage of energy for maximum utility, although the scale is different. For EV, the storage period is minutes, but for geothermal it would be seasonal. The smart part of SHIGS is the need for sensors and software to optimize the energy available for the particular end-user and climate conditions. Sensor data would be transmitted through the internet to more central locations for smart surveillance and smart decision-making. Because of the vast differences in climate between July and January, systems must operate over a wide range of power and heat demands.

What are some of the major issues that need to be addressed in the pursuit of SHIGS for remote communities? The researchers are looking at many aspects of this question; from heat pipes for conductive heat transfer into the rock mass to recharging the heat repository with solar thermal collectors in the summer. The major geomechanics issues that arise are:

- Understanding how to stimulate, operate, and predict the behavior of a deep geothermal heat mining system involving two or more deep wells in fractured rocks for a 30- to 40-year lifespan.
- Proper sizing of a heat repository at moderate depths (200-500 m deep?) in dense rocks using conductive heat transfer to store and access heat with a ground-source heat pump system.
- Improving borehole drilling time and cost outcomes, as the installation and stimulation of deep boreholes are the costliest elements in the system.
- Identifying and exploiting sources of waste heat (e.g., from diesel power plants) or collection of heat (solar in the summer months) in effective ways to manage the heat repository.
- Predicting stress changes from temperature changes at appropriate scales; and understanding how these affect flow rates in fractured rock masses, induced seismicity, and project life span.

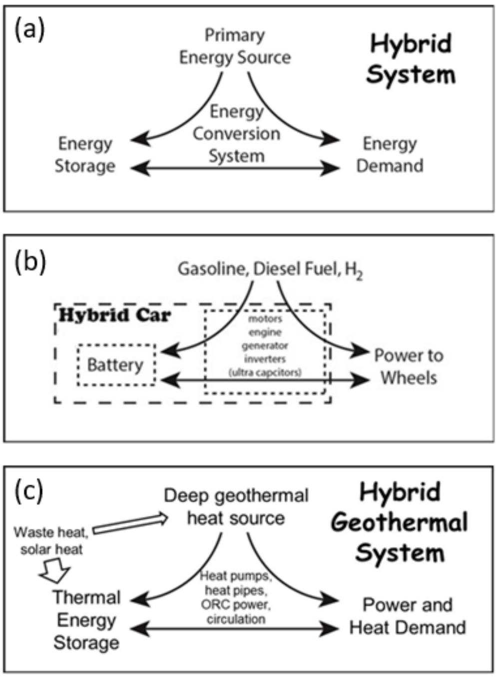

Figure 8: (a) The Hybrid System Concept: Sources – Conversion – Storage – Uses; (b) a hybrid system using a battery for energy storage; (c) a hybrid geothermal system.

The hybrid car analogy is worth explaining in more detail. Figure 8 clarifies 1) the concept of a hybrid system (i.e., a system with energy conversion and storage); 2) the hybrid car with a gasoline engine and a battery; and 3) the hybrid geothermal system. Figure 8b could have included a plug-in recharger for the hybrid car, just as we "plugged in" some available waste heat in the SHIGS system (Figure 8b) to recharge it seasonally. Figure 8c, shows the ORC power engine must be able to operate at its peak efficiency in the coldest months, so the optimization approaches must be geared to this period, but for effectiveness, waste heat is not discarded, it is stored whenever possible. The analogy with a hybrid car is clear, but the geothermal system is more complex because of different energy sources, a dramatic seasonality in the energy needs, and the additional complexity associated with geological systems.

In summary, for isolated communities in the north, where the sun is dark for many months and wind power is not baseload, there are few viable renewable energy options available for the full year. Researchers at UW believe that the SHIGS approach may provide part of the solution to the need for reliable, resilient local energy management in the north, for civilian and for military needs.

4. PROVINCIAL AND TERRITORIAL GOVERNMENT INITIATIVES

4.1 British Columbia (contributed by Bastien Poux (bastien.poux@gmail.com))

Geothermal energy exploration in Canada began in British Columbia's high temperature geothermal systems. In particular, the volcanic Mount Meager (part of the Garibaldi Volcanic Belt), with extensive hotsprings, was an early target where exploration took place for more than a decade (Hickson 2017). This volcanic massif is in southern British Columbia and is the site of BC's only wide-diameter geothermal drilling. It continues to be of exploration interest today due to the high temperatures (up to 260 °C) reached in some of the wells. There are now seven wells, six of which are on a lease held by Toronto-based Polaris Infrastructure. Of these wells, MC1 successfully supported a 250-kW power pilot plant tested for 40 days in 1984. Polaris is interested in ways that the wells and lease area could be used for research purposes. A workshop was held October 13, 2018 to review the available information on the system (Hickson et al. 2018e).

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. Over the past ten years, GBC has dispersed close to CDN$1Million dollars in research funds since inception of the program and committee. Despite the long history of BC projects and high-quality resources such as Mount Meager, geothermal power generation projects have not advanced in British Columbia over the past decade. In 2016, GBC decided to expand its focus from high temperature systems to also include direct use. Several projects were funded to provide a roadmap for communities to follow in order to help them initiate and carry out geothermal projects (Hickson et. al. 2017). A website was also established with training material to help developers (Hickson and Proenza 2017).

In 2019, GBC contributed CDN$500,000 in funding along with provincial and federal contributions to a new project in the Garibaldi Volcanic Belt (Grasby 2019; Geoscience BC 2019; Figure 9). This belt, which includes Mount Meager, will focus on reducing the exploration risk in one of the highest potential geothermal regions of Canada. NRCan's Geological Survey of Canada (GSC) is the lead agency while GBC as well as NRCan's Renewable Energy Development Initiative program are providing funding. The project will take knowledge from the Mount Meager research to apply to the overall Garibaldi Volcanic Belt, while developing new predictive tools for finding permeable aquifers at depth. Results will also be used to develop 3-D resource models using the Leapfrog Geothermal software by Seequent, allowing for a greater visualization and interpretation of all the geoscientific data in one place and to plan for the next stages of the project. The field work was started during the summer of 2019 with the acquisition of magnetotelluric and gravimetric sites as well as the installation of seismic stations.

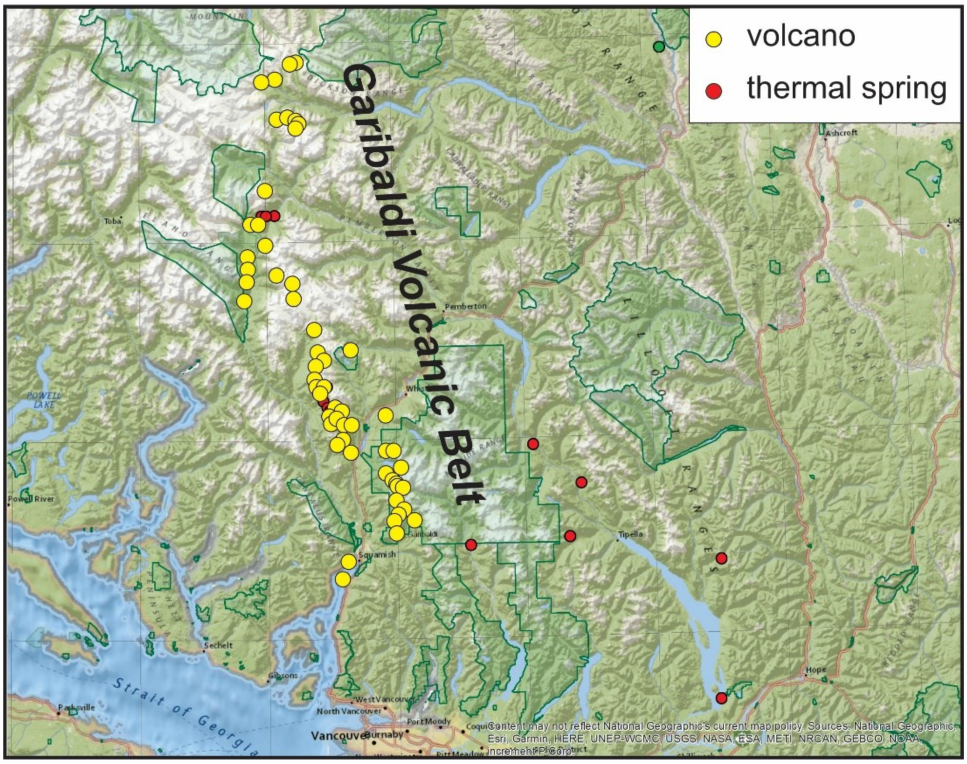

Figure 9: Generalized map of the Garibaldi Volcanic Belt volcanoes (yellow) and known thermal springs (red).

In 2019, Geoscience BC awarded several scholarships for geoscience related research projects, including two in the geothermal energy field. The first one will look at crustal stress and fault kinematics in southeastern British Columbia and its implications for fault permeability and geothermal energy resources. The results of this work will be valuable in assessing geothermal energy potential for a small town in the region studied in British Columbia and will contribute to the understanding of subsurface fluid flow in orogenic belts. The second project will evaluate the hydro-geothermal setting of the Sloquet thermal springs and intends to determine the depth or origin of thermal fluids and the temperature distribution at depth, as well as the structural controls that characterize the system.

A techno-economic assessment of geothermal energy resources in the sedimentary basin in northeastern British Columbia was also completed by researchers from The University of Victoria who evaluated four areas favourable for geothermal development. The sites are at Horn River, Clarke Lake, Prophet River and Jedney. In the Clarke Lake Gas Field Reservoir Characterization report, researchers from the University of Alberta analysed the potential of the depleted Clarke Lake natural gas field for its potential as a geothermal reservoir.

4.1.1 Clark Lake Reservoir (contributed by John Ebell (john.ebell@barkley.ca))

As noted above, in the far northeast of British Columbia the Clarke Lake Field has been the focus of several technical studies funded by GBC (Arellano 2018; Palmer-Wilson et al. 2018a; Renaud et al. 2018). NRCan has also funded a "Conceptual Design and Feasibility Assessment" through one of its national programs. This project is a depleted natural gas reservoir being redeveloped for its geothermal energy potential. The Clarke Lake Reservoir, within the Western Canadian Sedimentary Basin, is the oldest and amongst the most abundant gas fields in British Columbia and after 60 years it is no longer a commercially viable petroleum producer. 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 are the Fort Nelson First Nation, and it is they who are the proponents for the Clarke Lake Geothermal Project.

The Clarke Lake reservoir is approximately 127 km^2 (49 square miles) in area. Within the defined Clarke Lake reservoir 154 gas wells have been drilled to depths in the range of 1900 – 2600 m. An abundance of geological data is one of the legacies that exist from this petroleum development. The middle Devonian dolomite aquifer that hosts the Clarke Lake Gas Field has long been known to exhibit relatively high permeability, water saturation and temperatures in excess of 110°C. Based on this data geothermal exploration is considered complete and project engineering is now progressing. The ancient coral reef is sprawling and elongated in its geography (Figure 10). Given the large geographic extent of the aquifer, the most likely development scenario would involve several smaller generation facilities clustered around groups of production wells. The project will employ binary organic Rankin cycle power plant technology.

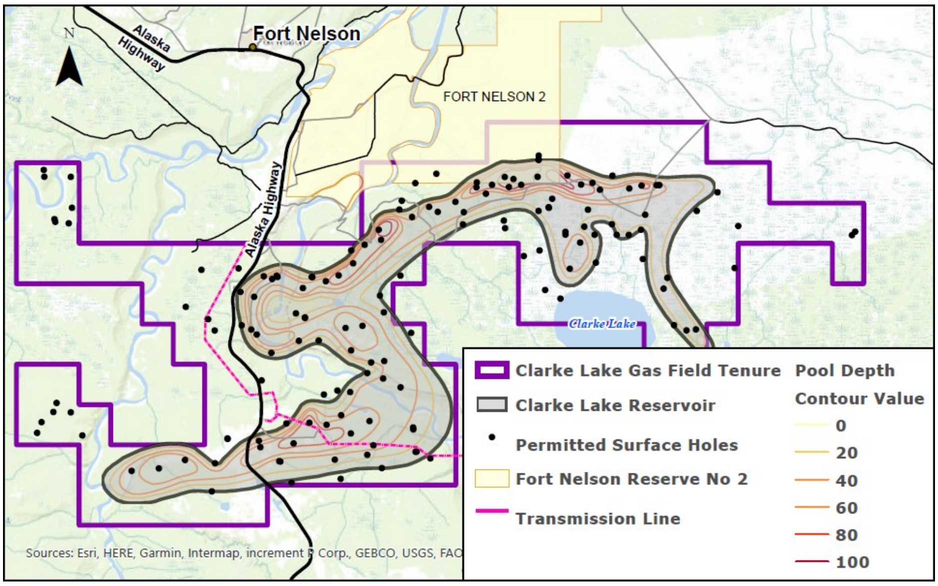

Figure 10: The Clarke Lake Reservoir, northeastern British Columbia. Project will take place within the confines of the reservoir outline.

The initial development began in summer 2019 with a focus on updating geothermal resource modeling and numerical simulations along with permitting and detailed business planning. Characterization well development is scheduled for the summer of 2020 with the development of a full-sized production well and the refurbishment of existing gas wells for reinjection. Following detailed engineering and financing in 2021, production well field development and plant construction are planned throughout 2022 and into 2023. Commercial operation is anticipated in late 2023. The expected output of this first plant is currently assessed to be in the range of 5 – 7.5 MW net generation capacity.

The 'brown-field' re-development of the Clarke Lake reservoir to a clean energy power project is expected to stimulate the regional economy, currently depressed from the departure of the oil and gas industry. Fort Nelson First Nation is excited to be providing sustainable, high quality employment opportunities for their youth, enabling them to remain in the region. The geothermal plant will displace the combined-cycle gas turbine generation plant that currently electrifies the region. The use of direct heat for agriculture, industrial processing and tourism is also being explored. Fort Nelson First Nation is excited to demonstrate the potential of geothermal energy to the cold northern regions of Canada and the Indigenous communities who live there.

4.2 Alberta (Contribution by Katie Huang (k.huang@albertano1.ca)**)**

There are several ongoing projects in various phases in the province. Technology based energy company Eavor, based out of Calgary, AB, have announced grants and partnerships to develop a demonstration facility of their closed-loop technology. Among the partners for this CDN$10 M project are the Shell New Energies Research and Technology Team and the Government of Canada via the Natural Resources Canada's Clean Growth Program and Sustainable Development Technology Canada. In 2019, Razor Energy Corp., another Calgary based company, announced funding for a geothermal project in northern Alberta. A $5 million contribution from NRCan's Clean Growth Program, and a $2 million contribution from Alberta Innovates, demonstrates a commitment by both levels of government to cleaner energy creation. Under the terms of the contribution agreements, NRCan and Alberta Innovates will assist Razor's development of a technically viable and commercially sustainable solution to recover geothermal waste heat from its hydrocarbon wells.

The Municipal district of Greenview (MDGV) located in west-central Alberta has also been working on geothermal initiatives. It commissioned a study of the potential of the Fox Creek area to Terrapin Geothermics (Terrapin), an Edmonton-based company. Terrapin followed this with other studies for local governments including the City of Grande Prairie. In 2019, the Government of Canada announced $25.45 million in funding through the ERPP for the Alberta No. 1 geothermal project, led by Terrapin in partnership with the MDGV.

These projects have been built upon over several decades of research for geothermal potential in the province (i.e., Bachu 1988; Gray et al. 2012; Weides et al. 2013; Hofmann et al. 2014a and b; etc.). This research has identified low-medium grade geothermal resources throughout Alberta with high potential for direct heat use as well as EGS.

4.2.1 Alberta No. 1 Geothermal Project (contributed by Catherine Hickson (c.hickson@albertano1.ca))

As shown by Weides and Majorowicz (2014; Figure 7) Alberta is known to have warm to hot brines in large extractable volumes from permeable, hydrocarbon-bearing units. In Alberta's northwestern region, the MDGV was actively supporting preliminary resource investigations within its lands such as at Fox Creek (Hickson et al. 2018c). These investigations led to the determination that there was an economically viable resource under the MDGV and, particularly, near a new light industrial park planned near the hamlet of Grovedale. Alberta No. 1 (as the project has been named; Hickson et al. 2018b and d, Hickson et al. 2019) will provide the industrial park and nearby facilities with both electrical and thermal energy produced by the project.

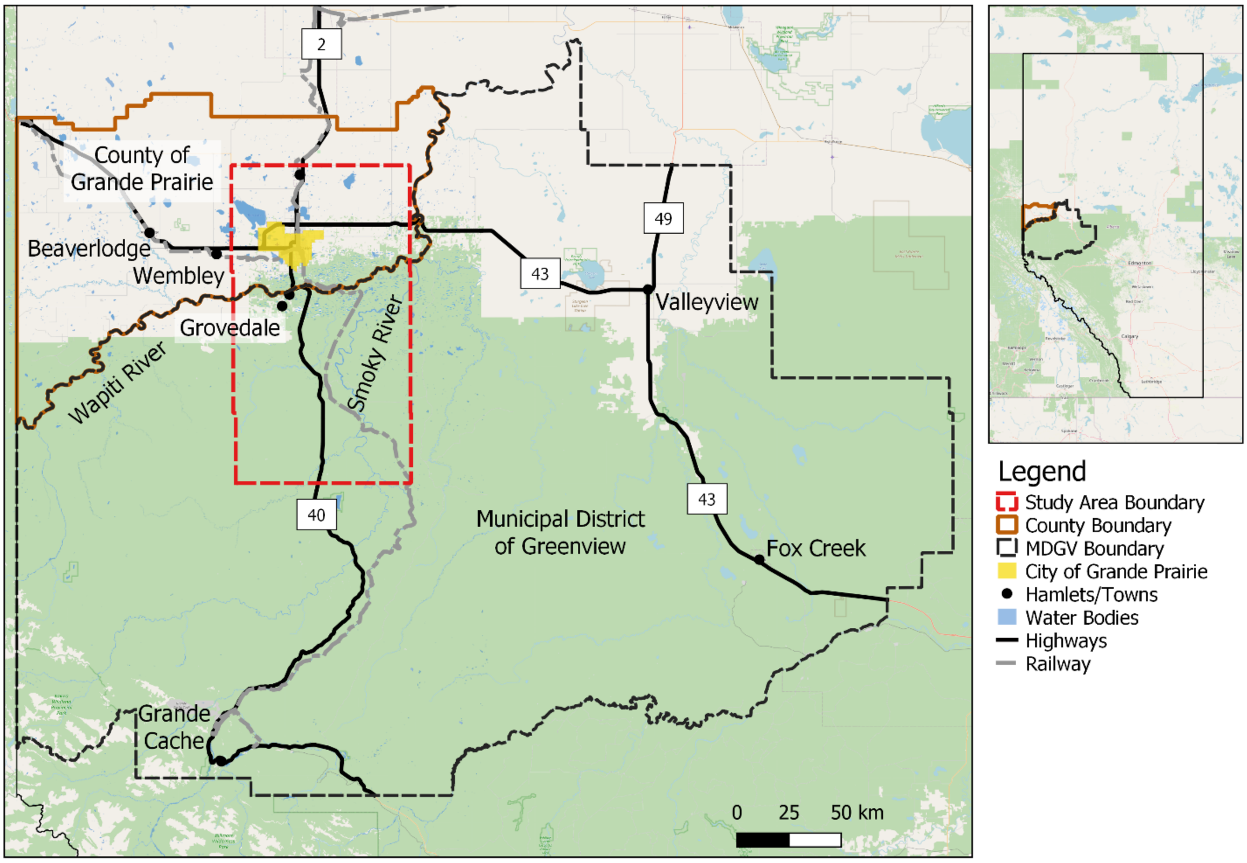

Figure 11: The Alberta No. 1 geothermal project is located near the hamlet of Grovedale, south of the City of Grande Prairie and within the Municipal District of Greenview and County of Grande Prairie. The study area boundary defines the area that was assessed for temperature and local stratigraphy.

The research suggests that temperatures above 110°C are attainable at depths of 3,500 m and below. The target formations at these depths are sedimentary and carbonate sequences below the Ireton formation and the Precambrian basement. Importantly, the targets are below the hydrocarbon and shale rich Duvernay Formation. Very few wells in the area have been drilled to these formations. . There are limited flow rate test data on the target formations but extrapolating from similar target formations elsewhere, it is anticipated that flow rates in 7-inch pipe will exceed 30 L/sand the total flow rate required for 8MWe (gross) generation is 300 l/s.

4.3 Saskatchewan (contributed by Janis Dale (janis.dale@uregina.ca) **& Brian Brunskill** (brianbrunskill@sasktel.net)**)**

The success story for geothermal electricity projects in Canada is the DEEP geothermal power project in southern Saskatchewan (Figure 7). The project is being supported by ERPP funding along with private sector investors. The first-of-a-kind in Canada, this Private-Public partnership project, located in southeastern Saskatchewan, is a few miles north of the United States border (Figure 7). This project builds on early direct-use projects in Saskatchewan. Along with Mount Meager in BC, federal and provincial funding focused on the University of Regina, which led to the drilling of a geothermal test well in the winter of 1978-79. The single test well was cased to 2034 m, and open holed to 2226 m. Over 40 papers and technical documents reporting on the efficacy of geothermal use for heating on the University of Regina campus have been written (U of R Energy Research Unit, Dr. Laurence Vigrass). The project was not completed, as the second well was never drilled but very important results were obtained that impact future projects in the WCSB.

The project showed the importance of the "Basal Clastic Unit" of the WCSB (Figure 6). These rocks consist of interbedded sandstones and shales and are of Cambrian-Ordovician age, making up the Winnipeg and Deadwood formations, referred to as the "Deadwood Aquifer". The aquifer is widespread, although varies in geological character as well as temperature (Figure 6). This work has shown that the temperature of the water available at the wellhead on the U of R campus would have a temperature of 58 to 59°C when pumped at a rate of 60 to 100 m^3/h. Reservoir water is a sodium-chloride-sulphate brine with total dissolved solids of 108,500 g/m^3. Corrosion testing showed that the water contains little hydrogen sulphide and carbon dioxide and, if kept free of dissolved oxygen, is not aggressively corrosive (Vigrass et al. 2007).

Pumping tests were also very successful with an indicated productivity index estimated at 0.11 m^3/h per kPa of drawdown (Vigrass et al. 2007). It is known that the water in the Deadwood Aquifer is stagnant, moving likely at a rate of less than one metre per year. Modeling completed for the original well indicates that thermal breakthrough would occur after 35 years of continuous pumping. The geothermal system planned now considers greater pumping rates to increase system capacity, and greater separation between the wells to increase system longevity. Operating at 60% capacity the system can allow over 70 years of exploitation. With this technical knowledge completed, efforts are now underway to resurrect the project to heat Kisik Towers, a new residence, being built on campus.

4.3.1 DEEP Energy's Power project (Contributed by Kirsten Marcia (kmarcia@deepcorp.ca) & Leo Groenewoud (lgroenewoud@deepcorp.ca))

While efforts are underway at U of R for their direct-use project, funding for DEEP (Figure 12) led to the successful drilling of the first geothermal test well in Saskatchewan. This well targeted the early Paleozoic age basal clastic reservoirs of the Winnipeg and Deadwood Formations and fractured Precambrian granite. Following the successful first well, DEEP commenced the 2019-2020 drilling and testing program which involved drilling four new wells to further define the geothermal reservoir and testing 3D seismic and airborne geophysical data. Results from the testing program indicated that the geothermal reservoir is multi-zonal, with both a fracture system and sedimentary resource.

DEEP then conducted the 2020 spring/summer flow testing program to test the temperature and flow rates from the Deadwood Formation. Results indicated that the reservoir is sufficient to support multiple geothermal power facilities. Shortly after, DEEP drilled the first horizontal well to a measured depth of 5672m (3450 m total vertical depth), which is the deepest horizontal well in Saskatchewan's history. Open hole testing was conducted using a coil tubing nitrogen lift test, and results indicated high permeability and flow capacity was in the order of 20 000 m^3/d and the highest temperature during open hole logging was 127°C.

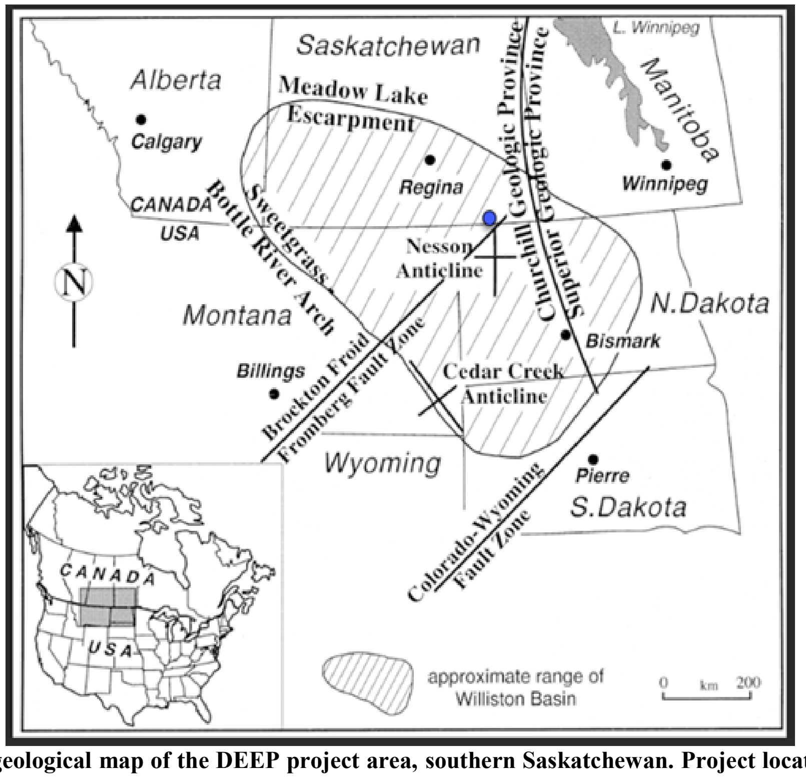

Figure 12: Schematic geological map of the DEEP project area, southern Saskatchewan. Project location is shown as a blue dot at the northern end of the Brockton Foid Fromberg Fault zone.

4.4 Nova Scotia (contributed by Catherine Hickson (cathie@ttgeo.ca))

In 2020 The Offshore Energy Research Association of Nova Scotia (OERA) put out a request for proposals to update the onshore geothermal potential of Nova Scotia. As stated in the RFP, the project will "compile and review available information to provide a preliminary opinion on the potential for geothermal development in Nova Scotia and to characterize the favourability of geothermal resource development across the province". This objective is posed for two basic categories of geothermal resource: (i) electricity generation, and (ii) heat production from abandoned mines or mid-depth reservoirs. The project ends in 2020, with results possible by the time of the GRC.

Interestingly, the province hosts one of the most successful long-term geothermal projects in Canada. The Town of Springhill has been utilizing geothermal energy stored in abandoned, flooded mine caverns, since the late 1980s. The Cumberland Energy Authority and the Government of Canada have recently invested in the development of a mine water geothermal business park on the site.

4.5 Yukon (contributed by Tiffani Fraser (tiffani.Fraser@gov.yk.ca))

Yukon Geological Survey (YGS) is evaluating the geothermal energy potential of the Yukon (Figure 13) to help determine the viability of developing these resources. Renewable power is not a top-of-mind issue for Yukoners, as the bulk of Yukon's power is generated from renewable sources (mainly hydro, with increasing components of solar and wind). However, projected power demands for potential new mine developments over the next ten to twenty years will exceed Yukon's current power capacity, and consultations around new hydro developments have met strong public opposition. Additionally, although the power grid is currently over 90% renewable, four communities are off-grid, and the majority of Yukon homes and businesses are heated with hydrocarbons. All hydrocarbons used in the territory are trucked from the south.

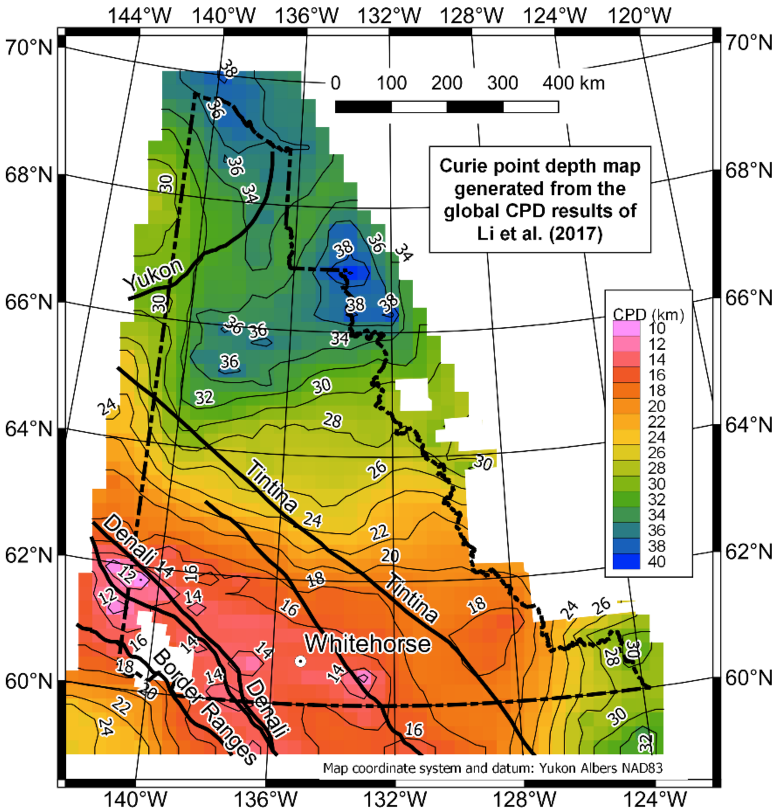

Figure 13: Yukon Curie point depth map. This map has been used to target additional investigations in Yukon (Witter et al. 2018).

Previous geothermal investigations in the Yukon include numerous regional and site-specific studies by the GSC (Grasby et al. 2012), Yukon Energy Corporation (unpublished studies) and the Canadian Geothermal Energy Association (CanGEA 2016). The current research builds on these studies and has four components:

- Modeling regional heat flow in the mid to shallow crust.
- Calculating potential heat production from young granites.
- Direct measurement of thermal gradient in two ground temperature monitoring wells; and,
- Geophysical surveys over an active deep crustal fault structure.

Heat flow was modeled by Witter and Miller (2017) by calculating Curie point depths (CPD) using public domain regional aeromagnetic data from NRCan (Figure 12). CPD estimates were subsequently improved upon by Li et al. (2017; Figure 13) using a global EMAG2 magnetic dataset as discussed in Witter et al. (2018). The Curie point, defined as the temperature above which a magnetic substance loses its magnetic properties, corresponds to a temperature of roughly 580°C for the commonly occurring mineral magnetite. CPD calculated for Yukon correspond well with the heat flow map of Grasby et al. (2012), with the shallower CPD occurring across southern Yukon.

Additional, shallow sources of potential heat were identified by calculating the heat generated from the natural radiogenic decay of U, Th and K in granites. Using the technique of Rybach (1981), heat-production values were calculated from existing whole rock geochemical data. Granites in southern Yukon locally have significantly higher heat production values than "average" granites (over $10\mu W/m^3$ vs. $2.45\mu W/m^3$ for an average granite). Notable are Cretaceous granites which have higher heat generation values compared to younger Paleogene ones. Of significant interest are plutons of the Cretaceous Seagull suite in south-central Yukon, where gravity modeling has enabled estimates of total contained heat energy (Colpron et al., 2021).

Direct ground temperature data were collected from two 500-metre-deep wells drilled between November 2017 and March 2018. One well is located midway between Takhini Hot Springs (46°C surface water temperature) and a granite pluton that yielded a heat-production value of 5.96µW/m3. The granite is thought to provide a heat source to infiltrating meteoric waters, possibly in permeable carbonate rocks. The second well targeted the Tintina Fault, a major dextral strike-slip fault that transects the Yukon. This location was selected to assess whether enhanced permeability in the fault creates a locally elevated geothermal gradient.

In 2019, the YGS acquired ground-based gravity and ELF-EM (Extremely Low Frequency Electro-Magnetics) data over a portion of the Denali Fault, near the community of Burwash Landing, southwest Yukon (a community which is diesel dependent for electricity). The purpose of the surveys was to 1) help estimate the variations in thickness of glacial overburden and other Quaternary sediments, and 2) differentiate subsurface lithologies (based on density and electrical resistivity) to aid in the interpretation of the complex structural relationships associated with the Denali Fault and subsidiary faults. The study has produced several targets, which will see drilling of temperature gradient wells in the spring of 2022. Meanwhile, work has been initiated to identify prospective areas along other major faults in Yukon to identify additional targets for temperature gradient wells.

4.5 North West Territories (contributed by Kathy Fiess (Yukon Government retired))

Recent federal and territorial government mandates to reduce GHG emissions associated with the use of diesel to generate electricity in remote communities has resulted in a renewed interest in the development of alternative renewable energy resources, including geothermal energy. The inclusion of this form of energy as a Northwest Territories Geological Survey (NTGS) research focus area will result in the delivery of the geoscience required to understand this resource and its potential contribution to NWT energy needs. To this end, NTGS has identified two geoscience project areas to focus research efforts. These project areas include Fort Liard and Yellowknife (Figure 14).

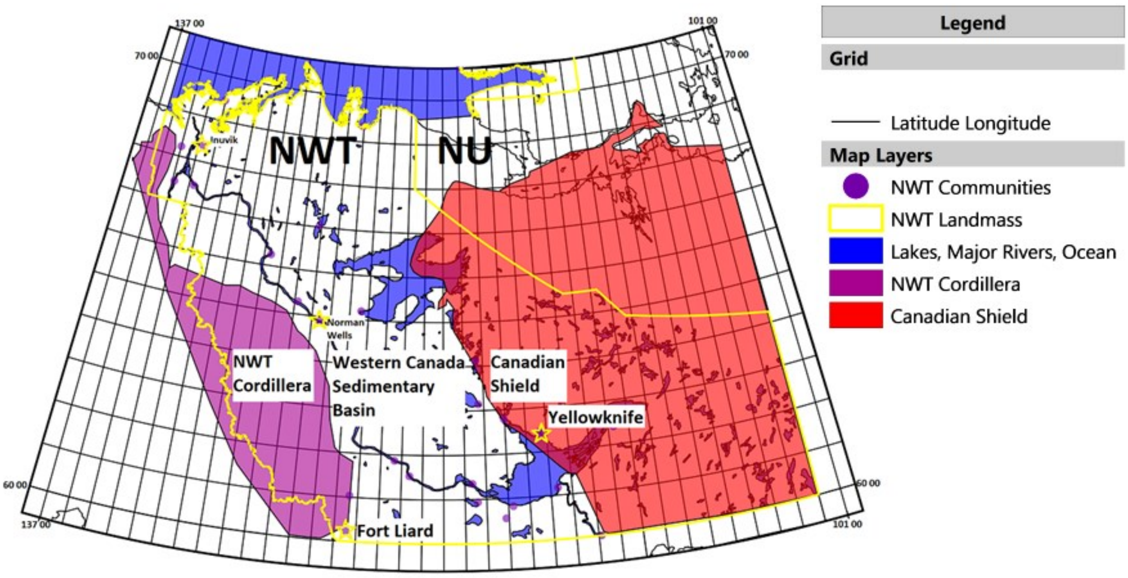

Figure 14: Location Map Northwest Territories (NWT). Fort Liard is an area associated with deep saline aquifers and has been the focus of hydrocarbon exploration and extraction. (NU=Nunavut).

The hydrothermal resource potential in the Fort Liard area is associated with deep saline aquifers. Such aquifers occur in Paleozoic and Mesozoic age basinal sedimentary rocks that overlie the Precambrian basement in that region. Exploration well bottom-hole temperatures near Fort Liard also indicate that the region is characterized by a higher-than-normal geothermal gradient of approximately 33 to 37°C/km (Grasby et al. 2013) (Figure 14). NTGS will conduct comprehensive reservoir characterization studies of potential resource and injector reservoirs using outcrop and core data, chip samples, geophysical well logs, regional bedrock mapping, and where available, gravity and magnetic susceptibility data. Seismic data will also be used to evaluate local structure and formation continuity, reservoir continuity (where possible), and formation depth and isopach mapping. Where relevant, resource volumes and productivity will be estimated. Reservoir risk associated with the potential resource and injector formations will also be evaluated.

The Con Mine, located in the City of Yellowknife (Figure 14), was the first gold mine developed in the Northwest Territories, Canada. Gold ore was actively mined from 1938 to 2003, and approximately five million ounces of gold were extracted from the mine. After the mine's closure, the City of Yellowknife contracted various technical studies during the early 2000s to examine the potential of the Con Mine as a geothermal heat source for the city. These studies determined that mine waters could have sufficient temperatures (up to and exceeding 30°C) to support a district heating project. NTGS has initiated a geoscience data gap analysis to identify additional research work required to assess project feasibility and geotechnical risk. Identified project geoscience research work will likely commence during the 2019-20 fiscal year. In addition to these research studies, Borealis has a project under development around the Hamlet of Fort Liard. Their website reports that a Front End Engineering Design (FEED) study has been completed

4.6 Nunavut (contributed by Catherine Hickson (cathie@ttgeo.ca)**)**

Nunavut, Canada's coldest jurisdiction (Figure 15) commissioned a geothermal feasibility study in 2018. This study, carried out by Saskatchewan-based Respec, completed the geothermal favourability map for Nunavut in October 2018 (Figure 16; Minnick et. al. 2018; Phase I) and was the first phase in identifying potential geothermal resources to offset the use of diesel for electricity generation and heat in the isolated communities of Nunavut. The objectives of that study were to gather existing data, identify data gaps, and conduct a geothermal resource assessment based on the existing publicly available data. The results suggest there is some potential for conventional geothermal in the western arctic in the Arctic Basin, but other parts of Nunavut will likely only support EGS or other non-conventional technology.

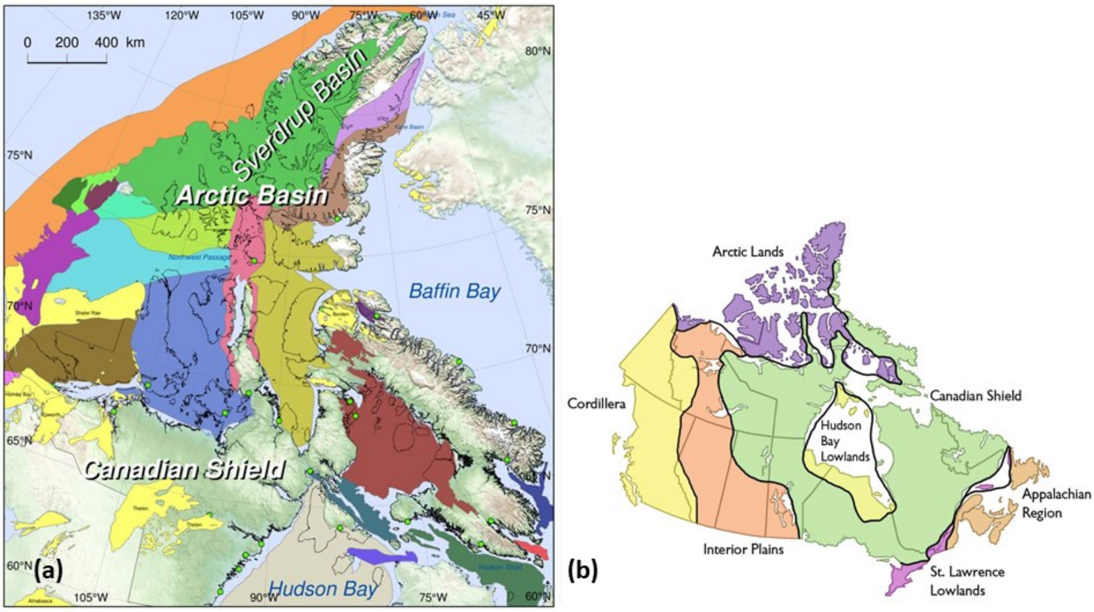

Figure 15: (a) Schematic geological map of Nunavut showing the major geological features. Solid coloured areas are sedimentary rocks of the "Arctic Basin" (purple in map (b) above). The Sverdrop basin is shown in green; topographic relief areas are underlain by metamorphic and crystalline rocks generally classified as "Canadian Shield" (green in the map above). (Topical Study RSI 2828) and (b) generalized physiographic regions of Nunavut (https://www.thecanadianencyclopedia.ca/en/article/nunavut) (Figure provided by Respec).

Following completion of the report, the Qulliq Energy Corporation asked for a follow-up proposal (Hickson et. al. 2018a) to carry the initial work forward in specific communities (Figure 16). These communities have a higher-than-average heat flow or significant enough loads (supplied through diesel generation) that the economic and carbon offset potential of replacing some of this generation and heat energy through tapping a deep geothermal resource are worth further investigation. The technical work proposed was divided into a Phase II and Phase III plan. Phase II work was grouped into two parts: (1) additional data gathering to support the targeting of temperature gradient (TG) well drilling and (2) the drilling itself.

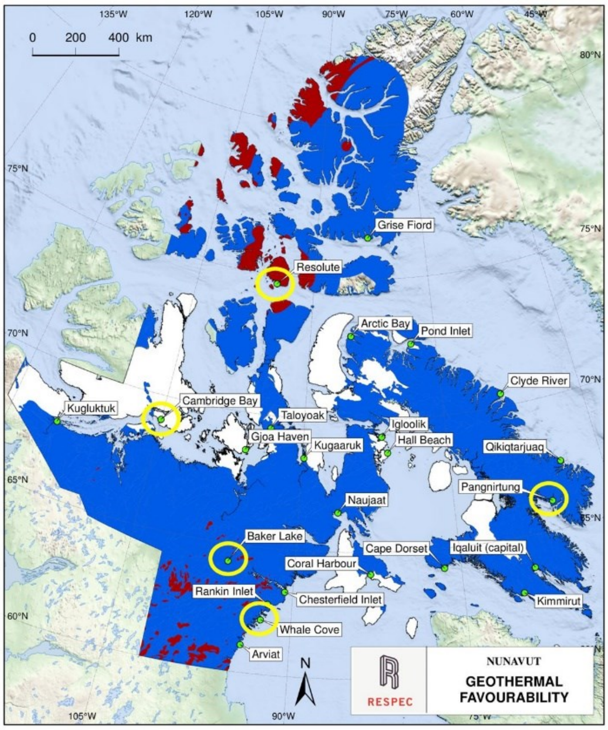

Figure 16: Geothermal favourability map for Nunavut (Topical Study RSI 2828) with the five targeted communities circled in yellow. Blue areas are typically underlain by crystalline rocks but may have a thin sedimentary cover in some cases. White areas are sedimentary sequences and red are intrusive rocks. Blue areas are considered to have low potential by conventional technologies; white areas are underlain by sediments of the Arctic Basin and areas shown in red have inferred temperature gradients slightly above global averages.

Suggested pre-TG drilling studies included conducting additional desktop data mining to fill the gaps identified in Minnick et al. (2018); performing field work to create detailed geological maps of site-specific areas for TG drilling; and collecting samples for physical rock properties (e.g., permeability, heat capacity, thermal conductivity, density, and magnetic properties), petrography, radiometric dating, soil gas, radon studies, and geochemistry of surface springs. It was suggested that this work could be augmented by seismic studies that focus on understanding regional structures and stress fields and possibly site-specific geophysics, such as gravity and magnetics. After data compilation undertaken as Phase II (1), integration, and analysis, and based on the detailed site-specific studies of Phase II (1) drilling one TG borehole in each of the identified communities would be undertaken (Phase II (2)). Phase III contemplates additional follow-up work based on the outcomes of Phase II as well as economic analysis of the feasibility of exploration drilling with either slim-hole or wide-diameter boreholes in select localities based on the data collected.

The proposed work in Nunavut as well as the work going in Nunavik are excellent platforms for technology advancement in Arctic Canada (cf. Raymond et al. 2015a and b). Technology challenges range from extreme temperatures to the challenges of permafrost. Mineral exploration has advanced some of the techniques needed in these environments (Figure 17) and northern adaptation required for remote mining developments (Figure 18), as well as communities spurring innovation.

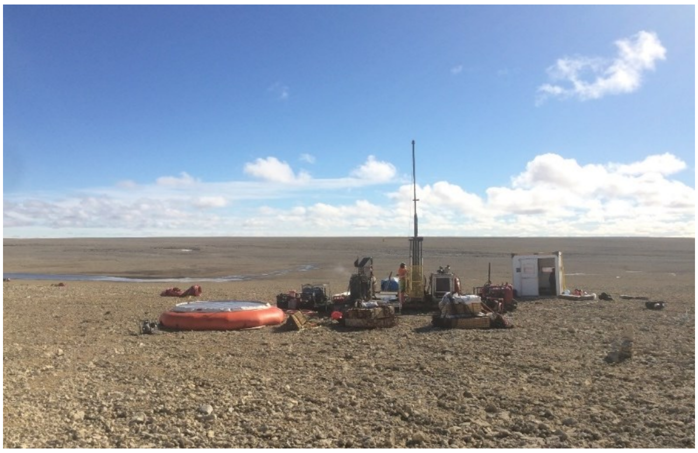

Figure 17: Typical Small-Core Rig Used for Mineral Exploration in the North. The red tank is used to hold drilling fluid. Drilling fluids must be heated and formed into a brine to suppress the freezing point of the drilling mud and prevent downhole freezing when drilling through permafrost.

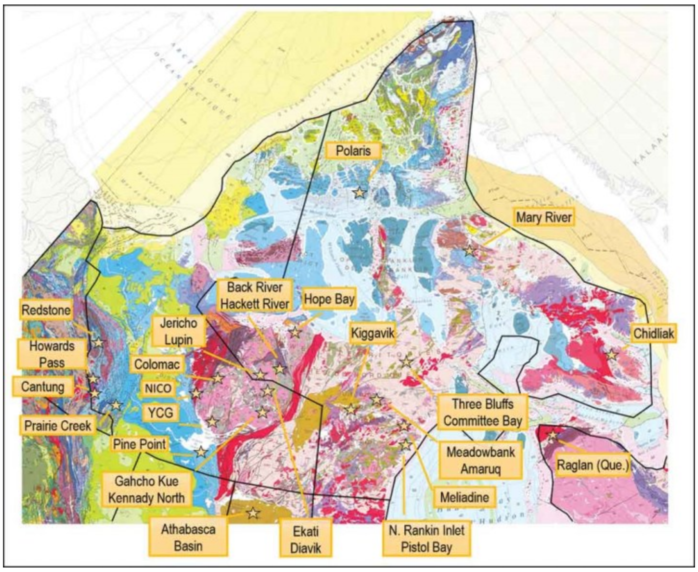

Figure 18: Major mines and exploration projects in Arctic Canada (http://www.miningnorth.com/mines).

5. FEDERAL GOVERNMENT INITIATIVES

The Federal Government has supported geothermal RD&I in Canada since the 1970s. This support has been largely awarded to the academic community and has reinforced National Science, Engineering and Research Canada (NSERC) funding, as well as the Geological Survey and Canada's national laboratories. Since the early 1970s federal funding has waned as more pressing national issues came to the forefront. However, the growing recognition of geothermal's base load capacity and overall energy generation potential in a world that is starting to value green energy is starting to produce funding results.

Advocates of geothermal energy development in Canada have long pointed out the advantages other renewables have received and how the development of industries in wind and solar have been supported. Federal recognition of the corporate challenges of geothermal projects from debt financing, high up-front capital costs, low rates of return and long time periods for return on investment (ROI) have been a long time in coming. However, under the recent ERPP program, geothermal is starting to get the support it needs to get out of the starting gate.

An additional challenge for geothermal projects in several provinces and territories is the absence of a regulatory framework for development. The Government of Alberta has shown dedication to support the development of the industry by the recent passing of Bill 36: The *Geothermal Resource Development Act.* The bill was introduced in October 2020 and received royal assent on December 9, 2020. It will outline rules and processes for responsible development of geothermal resources, establish the legislative authority for land use and liability management, protect landowners and mineral rights owners, and establish government's authority to receive revenues (Government of Alberta, 2020).

6. CONCLUSIONS

The foregoing summary of activity and projects in Canada is not complete but should give the reader a sense that activity in Canada is indeed on the increase with three important power generation projects and associated direct-use applications either in or near development. These projects are supportive of, and indeed have been informed by, the significant academic work already completed or being undertaken, as well as the studies at Canadian National Laboratories such as the GSC. We want to emphasize that all of the current work builds on the significant volume of research spawned since the 1970s.

Geothermal energy production, when well managed, is generational in its time frame. The recent federal funding support for DEEP is an important step forward in recognizing these long-term benefits and their commercial value. The challenges of geothermal projects from debt financing, high up-front capital costs, low rates of return and long time periods for return on investment have been slowly fading, to be replaced by the growing recognition of the value of base load power with generational timeframes. ROIs might be slow in coming but will continue for decades. The value of the carbon offsets and energy transition in a cold country with a sparse population will continue to manifest themselves as Canadians make efforts to reduce GHG emissions in a country where, for all practical purposes - heat is life. By accessing earth's naturally occurring heat and putting it to useful work, Canadians will continue to contribute to the global economy and address their commitments to greening that economy.

Geothermal can and should be the leading renewable energy source in Canada's portfolio of carbon reducing, industry "greening," renewable energy sources. With significant areas of the county underlain by the WCSB and other sedimentary basins in the east and north, Canadians have the "low-hanging fruit" to explore and develop in the short term. With huge experience in drilling technology, and some very cold and dark parts of the globe, Canada should be *the* global leader in low to medium temperature geothermal development, providing the blueprint to a sustainable, greener future for all global inhabitants.

For Canadians this is not about a competition between technologies or hydrocarbon versus geothermal energy – we need all of them! This is about preserving our hydrocarbon resources for the energy dense and unique chemical applications that only they can fill. It is about not wasting this valuable hydrocarbon resource on heating our homes. Geothermal energy development is about a sustainable and ecologically sound way to preserve our future and our children's future. This is about using the right resource for the right application. We hope that at the time of presentation of this paper at the World Geological Congress in Iceland, Canada will have even more positive information to report about its geothermal development both at home and abroad.

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