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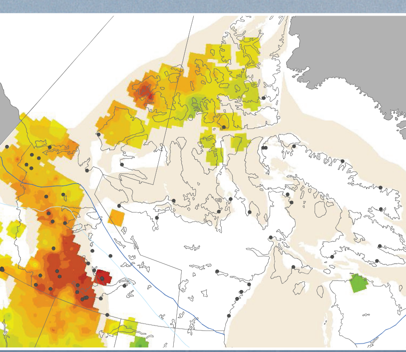
Geothermal Energy Potential *for* Northern Communities

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1. INTRODUCTION

1.1 Purpose

Remote communities of northern Canada (Fig. 1.1) are not connected to the North American electrical grid and instead typically rely on local generation for provision of electricity, and fuel combustion for heating. These communities experience high energy costs due to the combination of very low average annual air temperatures and high transportation costs for fuel used in heating and electrical generation. Northern communities typically have low populations (tens to a few thousands), making for additional high per capita capital costs for installation of generating capacity. These factors have driven interest in development of local energy supplies. A variety of options have been examined to date, ranging from small-scale hydro power to wind generation. However, usage of local geothermal energy resources has not been fully considered.

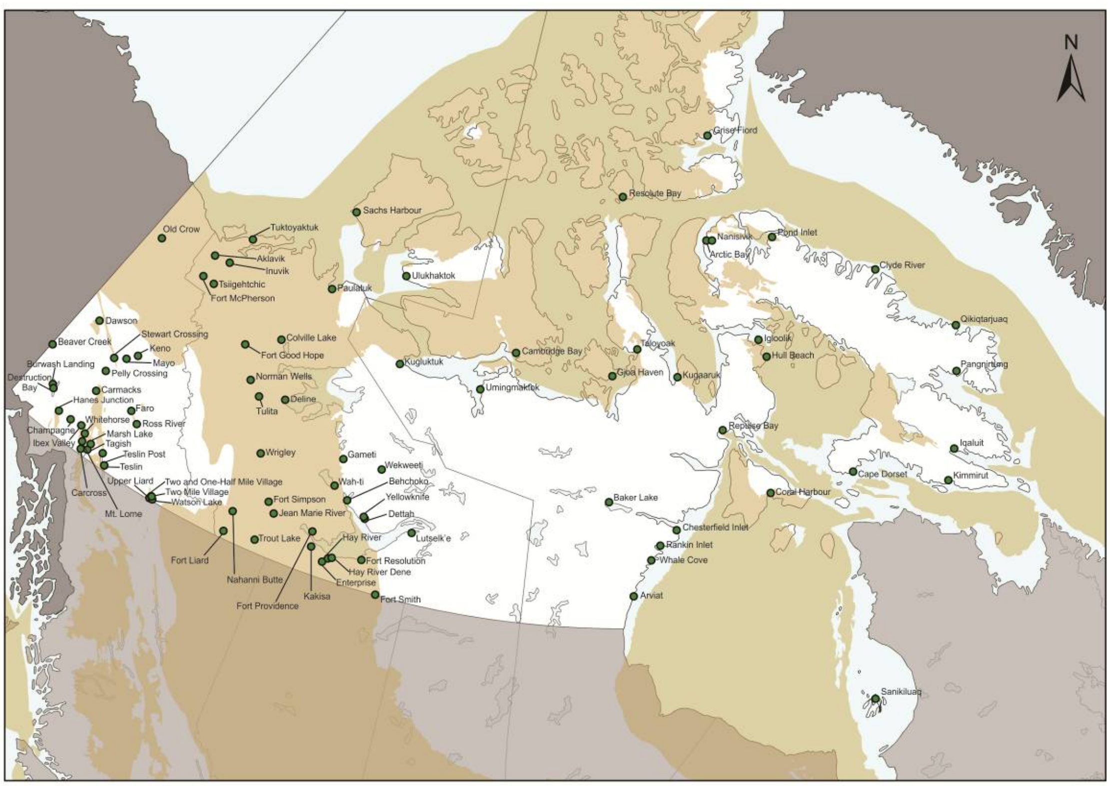

Figure 1.1. Map of Study area showing northern communities. Brown colour represents sedimentary basins of northern Canada where geothermal potential will be highest.

Recent studies have shown enormous geothermal energy potential spread over broad regions of Canada (Grasby et al., 2011a). This energy resource can be used to directly generate electricity with modern high efficiency heat exchangers (>90% efficiency) as well as for direct heating applications. Some northern communities are already assessing local potential for electrical generation (e.g. Fort Liard) as well as district heating (e.g. Yellowknife). The intent of this report is to examine which northern communities have the greatest geological potential for geothermal energy development to support local energy demand, along with providing an initial assessment of the economic viability of geothermal energy resources, for both: a) a realistic range of the low enthalpy heating systems, and b) electrical power generation from high temperature resources.

1.2 Geothermal Energy

Geothermal energy originates as heat generated in the Earth's interior by radioactive decay of three key elements (Uranium, Thorium, and Potassium), along with remnant primordial heat derived from formation of the planet. Heat generated within the planet conducts naturally from the interior to the surface. This creates a temperature gradient within the solid earth, with a progressive increase of temperature with depth. Several geologic factors control the rate at which temperature increases with depth (known as the geothermal gradient). This includes the rate of heat generation, along with the ability of rocks to conduct heat to surface (known as thermal conductivity). Rocks with lower thermal conductivity will act as a blanket and 'trap' heat, increasing temperatures at depth. In contrast, rocks with high thermal conductivity will rapidly conduct heat to surface, lowering temperatures at depth. These factors contribute to making a geothermal resource, where as additional factors influence whether or not that resource can be produced as an economic energy reserve. To produce heat from depth a carrier fluid is required. The fluid is heated as it moves through hot rocks, and then produced to surface (Fig. 1.2). At surface a variety of technologies can then be employed to convert that heat energy to a usable energy resource (ranging from electrical generation to direct heating). Rocks at depth therefore require high porosity (the percent of a rock that is void space that can hold fluids) along with high permeability (a measure of how easily fluids can move through geologic materials). These factors go towards forming a geothermal 'reservoir'. Finally, a key economic factor is the depth of drilling required to reach a suitable reservoir of hot water, along with the risk factor of finding such reservoirs at depth. While these geologic factors can create barriers to geothermal development, advances in technology are reducing the severity of these barriers. As such geological environments suitable for exploitation of geothermal energy resources are broadened. Currently geothermal energy is used globally as an economically competitive source of energy. A key advantage of geothermal energy, compared to other renewable energy resources (e.g. solar, wind), is that it provides an extremely reliable base load power supply, providing particular value for geothermal developments as an energy supply for off-grid remote communities.

Conversion of geothermal energy to a usable power source is a function of the resource temperature. For geothermal reservoirs above 80 °C (medium-temperature), electricity can be generated by means of a binary cycle plant (DiPippo, 2004), where a liquid with a low boiling point is “flashed” or vapourised by geothermal heat in a heat exchanger, and then passed through a turbine coupled to a generator (turbo-alternator) (Barbier, 2002). The efficiency of these systems is generally low (less than 6% (Barbier, 2002)), but they still provide a low-cost and reliable means of electricity generation from medium-temperature reservoirs (Barbier, 2002; Bertani, 2005). Higher temperature geothermal resources, exceeding ~150 °C, will form steam when the fluid is brought to the surface via a well as its pressure decreases. The steam can then be passed directly into a turbine to produce electricity. Only a fraction of the fluid is flashed to steam, and the remainder is boiling water (Barbier, 2002) that must be removed in surface separators. This remaining high temperature resource can be used for direct heating.

Moderate to high temperature geothermal resources can also be utilised for direct heating applications, such as space heating of buildings and greenhouses, industrial processes, drying of agricultural products, aquaculture, and thermal spas and pools. These can be either purpose built systems or as secondary usage of ‘waste’ heat from geothermal electrical generation facilities.

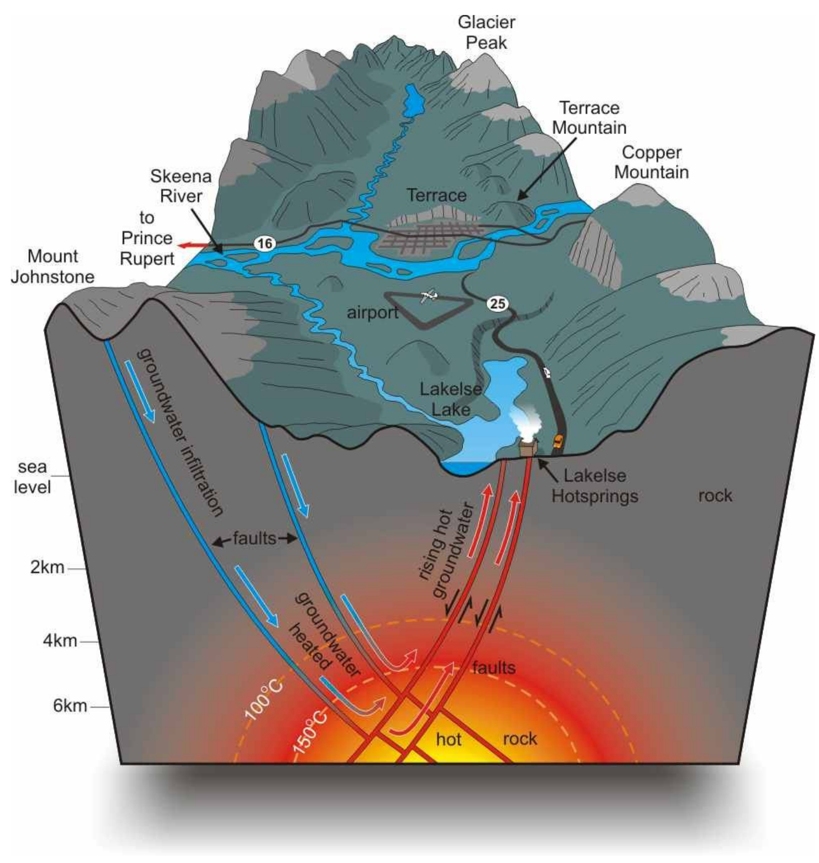

Figure 1.2 Schematic diagram showing deep circulation and heating of waters by a geothermal system at Lakelse, B.C. Drawing by B. Turner.

More recently interest has increased in Enhanced Geothermal Systems (EGS). Until recently, geothermal power systems have only exploited high temperature resources that have a naturally occurring reservoir of fluid that can be produced to surface. However, the vast majority of geothermal energy within drilling reach is in dry and non-porous rock. EGS technologies "enhance" and/or create geothermal resources through hydraulic stimulation. Several international programs are examining EGS systems in France, Australia, Japan, Germany, the US, Switzerland and the UK. The Cooper Basin development in Australia is the largest EGS project in the world, with the potential to generate 5,000–10,000 MW. Recently the EGS potential for Northern Canada was examined by Majorowicz and Grasby (2010a).

1.3 Previous Work

To date two geothermal energy projects have been examined in the NWT; 1) the Con Mine project for district heating in Yellowknife, and 2) a conventional thermal-electric generating system for the town of Fort Liard. While both projects remain in a planning stage, they promise to be the first geothermal developments in Canada's north.

Previous estimates show tremendous geothermal energy potential across Canada (Majorowicz and Grasby, 2010b, Grasby et al., 2011) as well as in northern Canada (Majorowicz and Grasby 2010a). Previous studies in northern Canada show the southern Mackenzie corridor (60 to 65 °N) is characterized by some of the highest geothermal gradients (40 to 50 °C/km) in all of Canada (Majorowicz et al., 1988, Grasby et al., 2009, Majorowicz and Grasby, 2010b). High geothermal gradients (>35 °C/km) were also found in the NWT north of 65 ^{O}N, east of the McKenzie Mountains. In the Beaufort Basin, gradients of 25 to 40 °C/km were found in the Tuktoyaktuk Peninsula (Majorowicz et al., 1996). High geothermal gradients (up to 45 °C/km) were also found in northern Yukon. In the Sverdrup Basin of the Canadian High Arctic heat flow is high and geothermal gradients locally reach 45 to 50 °C/km (Majorowicz and Embry, 1998).

A previous geothermal assessment for the NWT was prepared by EBA Engineering Consultants Ltd. (2010) in which they produced a geothermal favourability map and accompanying report for the Government of NWT (Environment and Natural Resources). This report provides a rating system based on pre-existing geothermal gradient data, and where this data is lacking, geology, seismicity, and thermal spring locations were alternatively used in assessing geothermal potential. The favourability map takes into consideration human factors including existing infrastructure (roads and electrical grids), community power sources, and community population statistics. The EBA report considers geothermal potential for power generation only, and does not consider heat exchange systems. Their findings indicate high potential areas within the Mackenzie River basin, significant to the communities of Fort Simpson, Fort Providence, and Hay River. Moderate favourability was determined for the Mackenzie Corridor, significant to Tulita, Deline, Norman Wells, and Fort Good Hope.

2. STUDY AREA

2.1 Northern Communities

Northern Canadian communities face a number of challenges in meeting their energy requirements. The majority of heat energy produced in northern communities is from burning of heating oil (See Figure 2.1A), which accounted for >80% of the total heat energy produced across the North in 2007 (annual percentages derived from the PanTerritorial Renewable Energy Inventory, 2007). Currently, 67% of northern communities consume electrical power provided by diesel generators, 31% are tied into local hydro grids with diesel backup, and 2% access local natural gas resources (Inuvik and Norman Wells only) (See Figure 2.1B). Northern communities are also faced with high transport costs for equipment and fuel, and higher maintenance and operating costs for facilities which may require specialized infrastructure, and face supply disruptions in difficult conditions. Utilizing renewable energy sources such as geothermal energy has the potential to increase both the economic and environmental sustainability of diesel and fuel oil dependent communities by reducing fossil fuel demand and associated energy costs.

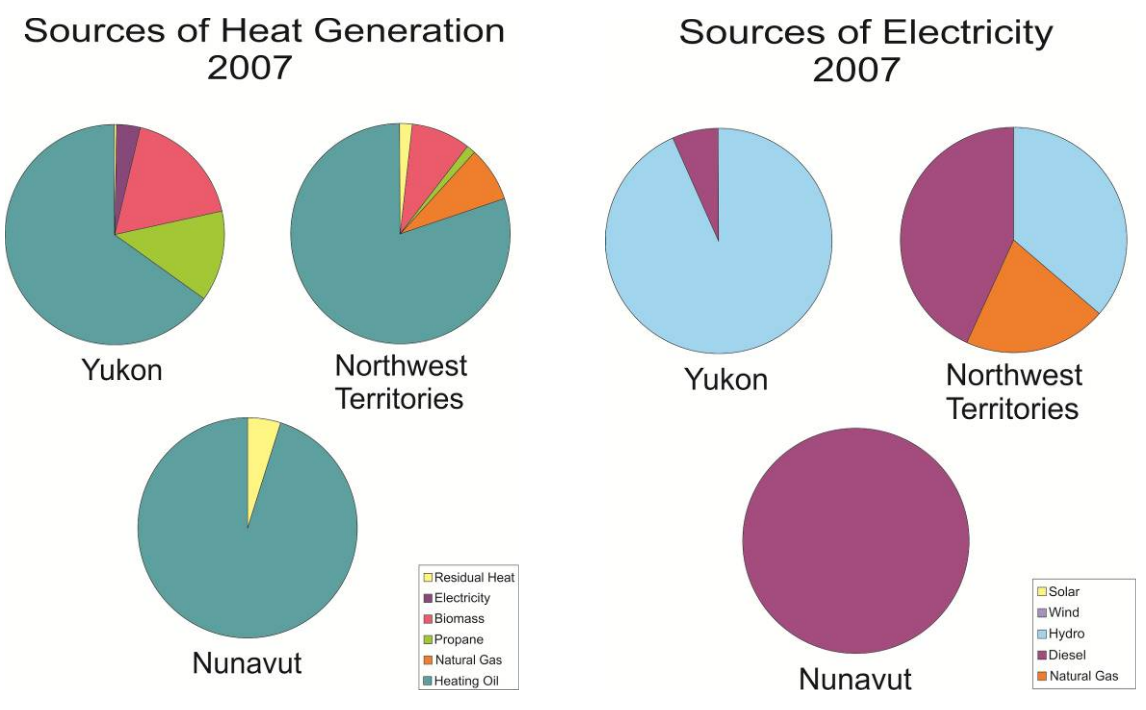

Figure 2.1 A) Sources of heat generation for the Yukon, NWT, and Nunavut, 2007 B) Sources of electricity, 2007; wind and solar sources do exit, but produce a very small fraction of total energy consumed. (PanTerritorial Renewable Energy Inventory, 2007)

This report is concerned with northern communities located in Yukon, Nunavut and the Northwest Territories (NWT). In total, 87 communities are located in these regions, with 33 in the NWT, 27 in Nunavut, and 27 in the Yukon. A list of community names and relevant statistics is provided in Table (2.1). Of these, only a subset are located in areas suitable for the establishment of geothermal resources Although geologic setting and thermal gradients are essential factors in determining the feasibility of geothermal resource development in a particular area, community specific statistics are also important elements to examine. These include population, total power usage, and per-capita energy consumption and cost.

Communities with populations greater than 1000 people (according to the 2011 CSC census by Statistics Canada) make up 6/33 (18%) communities in NWT, 2/27 (7%) communities in the Yukon, and 11/27 (40%) communities in Nunavut. The largest of these include the capital cities of Whitehorse (23,276), Yellowknife (19,234), and Iqaluit (6,699).

Total energy consumed by a community includes residential, general service (government and businesses), street lights, and industrial energy use. Total energy use provides a gross, first order perspective on energy demands within a community. Overall, total energy use in 2011 was 801,549 MWh across the North; 345,061 MWh for communities in the Yukon, 301,284 MWh in the Northwest Territories, and 155,204 MWh in Nunavut (See Table 2.1 for a complete listing of total power usages). Communities associated with the greatest total energy use include the capital cities with greatest population; Whitehorse (249,911 MWh; including Ibex Valley and Mt. Lorne), Yellowknife (160,012 MWh), Iqaluit (50,483 MWh). Communities consuming the least amount of total energy include Johnson's Crossing (87 MWh; a cottage community of 15 people with seasonal occupation, and therefore low energy use), Jean Marie River (population 64; 226 MWh), Keno (population 28; 351 MWh), and Kakisa (population 45; 393 MWh).

To consider power costs relative to population, industrial power usage is excluded. While power usage is greatest in communities with larger populations, the cost for conventional energy tends to be considerably greater for smaller communities. For example, energy costs at Colville Lake (population 149) amounted to $1783.92/MWh in 2011, versus $590.98/MWh in Fort Simpson (population 1238). This disparity is largely due to the fact that the cost of infrastructure, fuel transportation, maintenance, and operation for conventional power facilities is divided among fewer people in smaller communities.

In addition, small and remote communities such as Colville Lake typically depend on diesel generators to provide power, which is substantially more costly than hydro-electric generation such as that available at Fort Smith (unsubsidized rate of $2/kWh at Colville Lake versus unsubsidized rate of $0.16/kWh at Fort Smith). While hydro-electric grids service 77% of communities in the Yukon, only 24% of communities are hydro-powered in the NWT due to the limited distribution of hydro-electric grids. Here, the Snare hydro grid services Yellowknife, Behchoko, and Dettah, and the Taltson hydro grid services Enterprise, Fort Resolution, Fort Smith, Hay River, and Hay River Dene, all closely spaced communities located in the southern NWT. For communities serviced by Northwest Territories Power Corporation, those connected to hydro-electric grids paid an average of $248/MWh in 2011, whereas communities using diesel generators paid an average of $911/MWh. The community which faced the highest per capita costs in 2011 (for which dollar values were available) was Sachs Harbour ($9133.93 per person/year), which is powered by diesel generators and is the most northerly and remote community in the NWT, located on Banks Island.

Territory governments do provide subsidies in order to equalize disparities in energy costs between communities, and to compensate for the overall higher costs as compared with communities in southern Canada. Even then, electricity and home heating costs in northern communities have been up to 10 times greater than the Canadian average (National Energy Board, 2011).

The high cost of existing energy sources make northern communities ideal for implementing alternative energy technology, although geologic setting and geothermal gradient ultimately dictate the feasibility of geothermal energy development. Given a suitable setting, communities which would benefit most from the implementation of geothermal energy resources are those which have high consumption due to large populations, and small communities whose members pay more per-capita and per-MWh. Diesel reliant communities, without connection to hydro grids, would experience greatest financial benefit. Heat exchange systems would be a benefit to all communities to reduce reliance on heating oil, especially those at more northerly latitudes, where average temperatures are lower.

2.2 Controls on Geothermal Potential in Northern Canada

The availability and type of geothermal resources existing in an area is determined by three interrelated factors: geothermal gradient, underlying geology, and the availability of a suitable fluid reservoir at the target depth (see Fig. 2.2). In northern localities, permafrost depth also plays a significant role in determining the viability of geothermal energy sources.

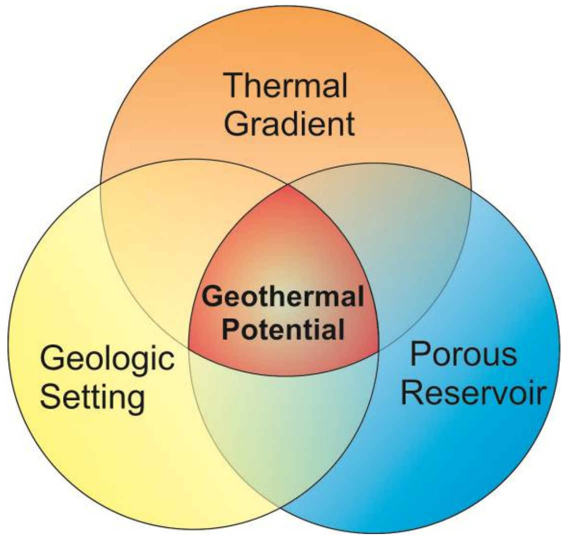

Figure 2.2: Interrelated factors necessary for potential geothermal resource development. High potential localities would ideally be situated in a geologic setting conducive to geothermal resource development (such as deep sedimentary basins), with high thermal gradients, and the availability of a porous reservoir at depth.

2.2.1 Geothermal Gradient

The most significant geothermal parameter in determining the feasibility of geothermal resources in a given area is geothermal gradient, or the rate of temperature increase with depth. It is necessary for conventional geothermal resources to be located within ~5 km depth, below which permeability is too low to allow for the flow of thermal fluids. Thermal gradients are estimated from temperature gradient logs and point measurements such as bottom-hole temperatures and drill stem tests, available from petroleum industry drilling reports. This type of data allows for estimations of temperature distributions across the region; however data sources are limited to areas of interest for petroleum exploration, leaving large areas of northern Canada with limited thermal gradient data. (refer to Figure 2.3 for data distribution). High geothermal gradients are known from the Mackenzie Corridor, Beaufort-Mackenzie region and localized areas within the Arctic Island basins (Fig. 2.4). In more northerly locations, geothermal gradients are depressed due to thick permafrost, which may extend ~0.2 to 1 km depth (Grasby et al., 2011a, Chen et al., 2010). Within permafrost zones, shallow heat exchange systems are not feasible. In addition, depression of geothermal gradients results in greater drilling depth required to reach viable thermal resources for power generation.

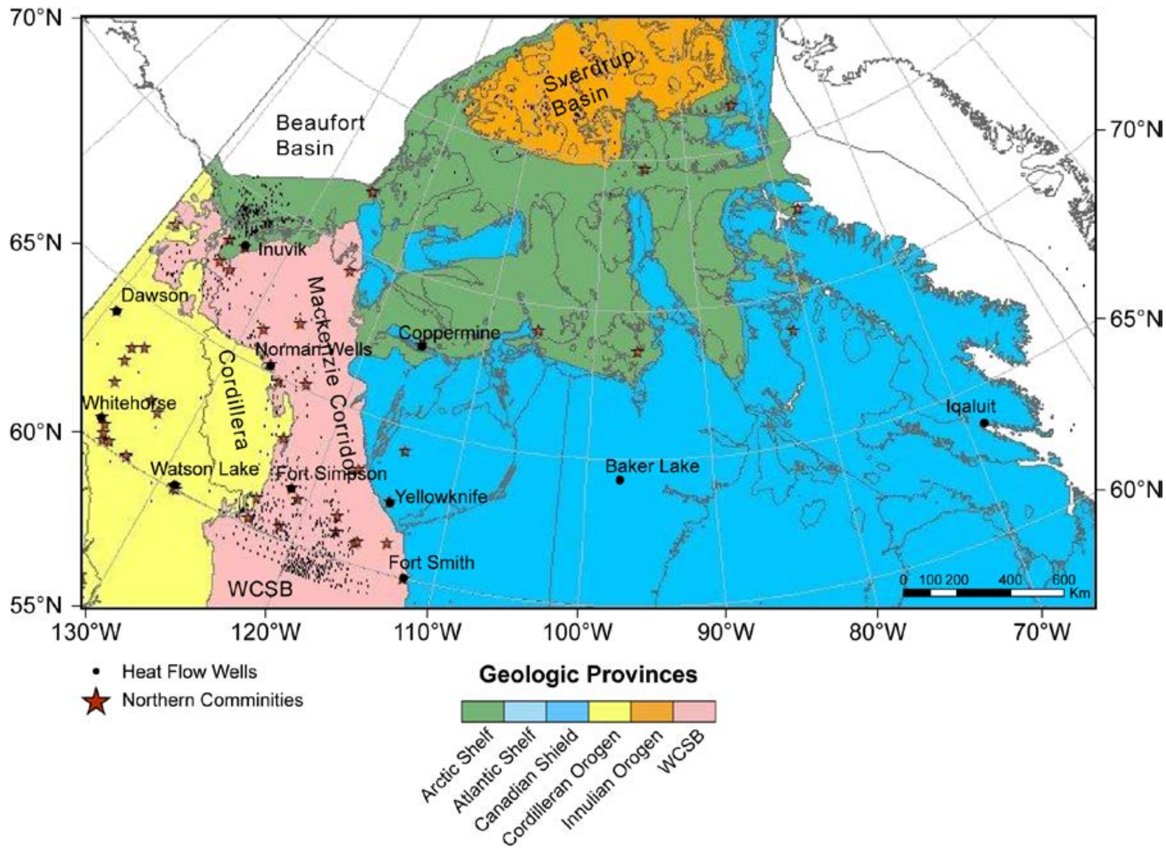

Figure 2.3: Map of northern Canada showing locations where heat flow values have been calculated from well data, along with main geological provinces and communities.

Geothermal gradients are generally greatest in areas with low thermal conductivity *and* high heat flow. Thermal conductivity of rocks is a parameter describing heat transfer from a heat source to a heat sink. Thermal conductivity is characteristic of different rock types, and is typically higher in crystalline rocks such as granites and gneisses (3.2 W/mK; Jessop 1990), and lower in sedimentary rocks (2 W/mK; Barker, 1996). Heat flow is highly variable across Canada's North; regional heat flow varies from values as low as 20 to 30 mW/m^2 in the Canadian Shield to values greater than 100 mW/m^2 in the northern Canadian Cordillera. High heat flow values (>70mW/m^2) are also found within the south-western Yukon and NWT, the Mackenzie Corridor, and Beaufort-Mackenzie area (Grasby et al, 2011a). High variability in heat flow values results from variability of heat transferred from the mantle (higher in areas of orogenic activity), as well as variability in radiogenic heat produced in the upper crust (greatest in young gneisses and granites).

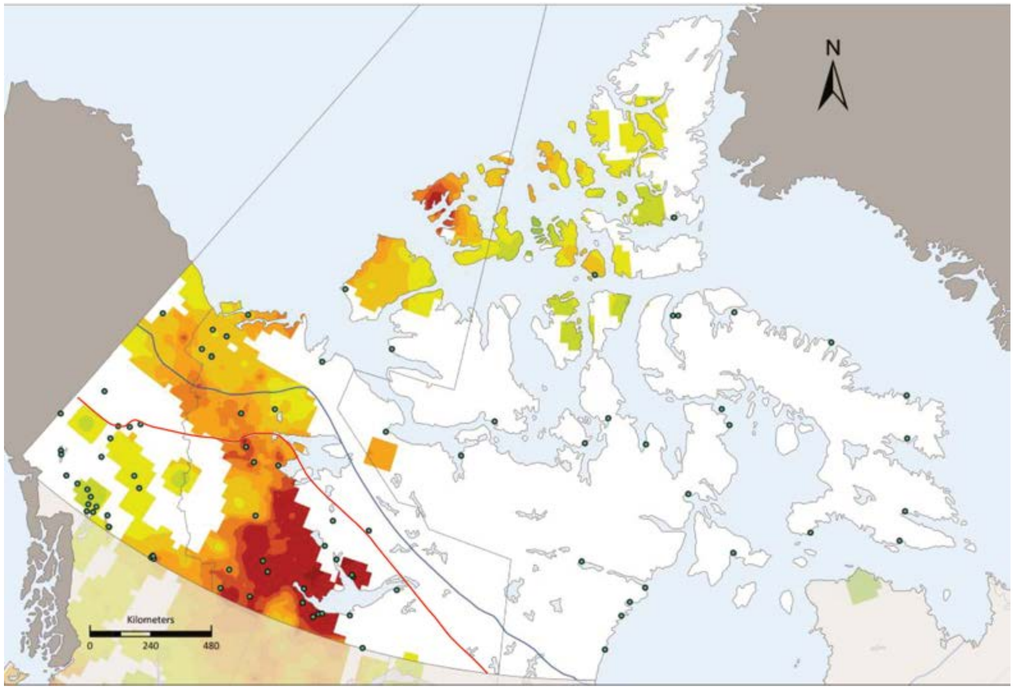

Figure 2.4. Map displaying geothermal gradients where it is possible to be determined within the study area. Community locations and extent of discontinuous and continuous permafrost in northern Canada are also shown. Geothermal gradients range from green (lowest) to red (highest). The red line denotes the most southerly extent of discontinuous permafrost, whereas the dark blue line denotes the most southerly extent of continuous permafrost. White areas have insufficient data to determine geothermal properties.

Geothermal gradients, heat flow, and thermal conductivity values for Northern Canada exhibit very high local and regional variability (Grasby et al, 2011). The high variability of these parameters is interrelated; for a given heat flow, the thermal gradient depends on thermal conductivity, and visa versa. For example, high heat flow occurs in the Yellowknife area, however, thermal conductivity is also high, resulting in a low geothermal gradient. Due to this relationship, general patterns of spatial variability of thermal gradients are evident and can be related to characteristics of the major geological provinces (Canadian Shield, Cordilleran orogenic belts, and sedimentary basins) (Fig. 2.3).

2.2.2 Geologic Setting

High temperatures required for low and high enthalpy geothermal systems are largely determined by variations in thermal conductivity associated with rock type. Sedimentary basins tend to contain rocks with low thermal conductivity (2 W/m K or lower), which create a thermal blanketing effect, increasing the geothermal gradient and reducing target depth. Conversely, crystalline rocks of the Canadian Shield and the Canadian Cordillera tend to have high thermal conductivity (3-4 W/mK). In particular, shield rocks have high conductivity values and low heat flow (~ 40 mW/m^2), making for very low geothermal gradients and subsequently, geothermal energy prospects are extremely low in the Canadian Shield.

However, the northern Canadian Cordillera, extending from the Yukon to the western NWT, exhibits high conductivity *and* high heat flow. Here, high heat flow is derived predominantly from the mantle in association with orogenic processes (Jessop, 1990). Highest heat flow values are associated with recent volcanic belts. These anomalously high local values are typically omitted from regional heat flow maps in order to avoid an inaccurate sense of high regional heat flow (Grasby et al., 2011). Despite this, young volcanic sites may increase geothermal potential for nearby communities, particularly in the south-western Yukon. Regardless of high heat flow values, the crystalline metamorphic and igneous rocks of the Canadian Cordillera have comparatively high conductivity relative to rocks found in sedimentary basins. As such, geothermal potential in the Canadian Cordillera is less predictable than within sedimentary basins, and would require more detailed, case-by-case investigation.

Geothermal resources associated with sedimentary basins are typically moderate to low temperature. Locally, however, temperatures exceeding 150 °C are known at depths as shallow as 3 km in the southern NWT – temperatures sufficient for electrical generation. However, basin thickness plays a significant role in determining geothermal potential, as conventional geothermal systems require thermal fluid source – typically water. Water-bearing sedimentary units must be at a suitable temperature for a given hydrothermal system, and therefore at a particular depth given the local geothermal gradient.

2.2.3 Fluid Reservoirs

Apart from requiring high geothermal gradients, conventional geothermal resources must have a suitably large body of permeable rock hosting thermal fluids (water or steam) that can be brought to the surface in order to extract heat energy. Typically, sedimentary basins contain a significant volume of porous rock that host abundant fluids. Given higher geothermal gradients associated with sedimentary basins, areas with thick sediment cover can have potential for high temperature water resources.

Fracture networks may also act as conduits for thermal fluids. In northern Canada, the Canadian Cordillera hosts hydrothermal fluids in fracture networks, as evidenced by thermal springs in the Yukon and southwestern NWT. However, these fluids have a limited, fault controlled distribution, restricting accessibility unless located proximal to communities. Alternatively, porous sedimentary units may have a wide spatial distribution.

Enhanced Geothermal Systems (EGS) do not require in-situ thermal waters. However, this technology is still developing, and may be problematic in tectonically active regions as induced seismicity had been correlated with the injection of external fluids. Therefore the employment of EGS in areas of high heat flow which lack naturally occurring fluids in the Canadian Cordillera is not ideal and would require thorough investigation.

2.3 Regional Geology

Geologic setting largely determines the potential for geothermal resource development. Knowledge of the regional geological framework of Northern Canada allows for the identification of geological regions associated with the best conditions to host a geothermal resource, thus reducing exploration risk. Northern Canada can be roughly broken up into three broad geological regions: The Canadian Shield, the Canadian Cordillera, and Sedimentary Basins (Fig. 2.3). A general description of the distribution and characteristics of these regions is provided here.

2.3.1 Canadian Shield

The Canadian Shield extends for ~8 million km^2 over central, eastern, and northern Canada, and is exposed over large areas of the central and eastern Arctic (Fig. 2.5). It consists of intensely deformed metamorphic and intrusive cratonic rocks of Archean and Proterozoic age. These rocks record a complex history involving multiple continental collisions and the amalgamation of crustal blocks. The shield is an area of low heat generation; due to the significant age of shield rocks (typically older than 2.5 billion years), radioactive elements hosted in the shield have undergone substantial radiogenic decay. In addition, the thermal conductivity of gneissic and granitic rocks is high, and any heat generated is quickly lost at the surface, lowering geothermal gradients. Further, shield rocks are dense and lack permeability, though in certain locations, fracture networks do allow for water accumulation and flow.

While geothermal data is limited for the Shield region, existing data demonstrates that this region has very low geothermal gradients (Grasby et al, 2011). Despite this, some (limited) settings have proved possible for low-temperature heat exchange systems, particularly at abandoned mine sites. For example, the City of Yellowknife has proposed the development of a heat-pump system at the Con Mine site. While these types of systems do provide limited potential for communities located on the Canadian Shield, however, low geothermal gradients and permafrost conditions in more northerly regions remain problematic.

Overall, communities located on the Canadian Shield are expected to have low potential for geothermal resource development. The low heat flow and high conductivity of this region prohibitively increases the required depth of drilling. Additionally, absence of reservoir units within the shield limits hot water sources. However, in areas of anomalously high geothermal gradient below the permafrost zone, such as is found in the Yellowknife area, it may be possible to capture the required heat at shallow depths via heat exchange systems. The economic feasibility of this type of development, however, is dependant on pre-existing void space generated through subsurface mining.

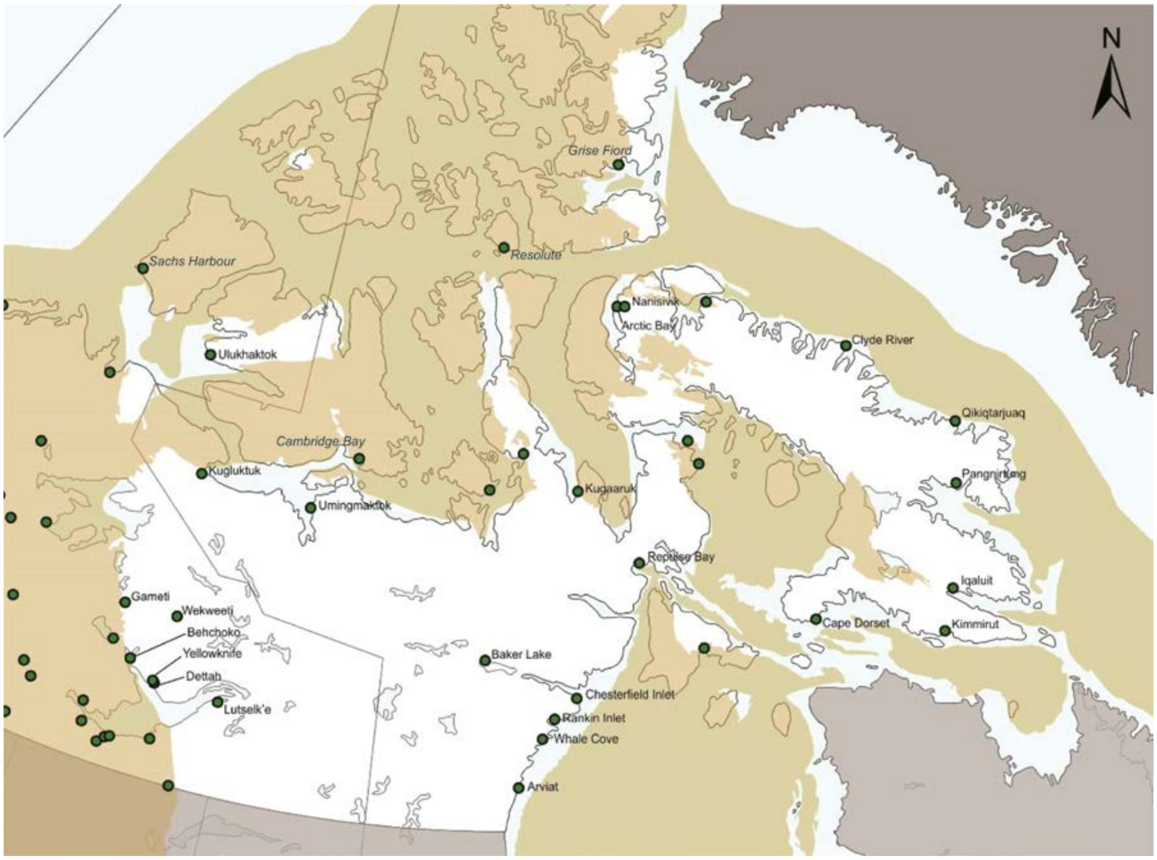

Figure 2.5: Communities located on the Canadian Shield, where sedimentary basins are shown shaded brown, and shield is unshaded. Communities in italics occur on sedimentary rock.

2.3.2 The Canadian Cordillera

The Cordillera is a mountainous region in western North America. In northern Canada, the Cordillera spans the Yukon and continues into the Mackenzie Mountains, western NWT. It encompasses an extensive area of mountain ranges, plateaus, and intermontane basins.

The Canadian Cordillera is a relatively young orogenic belt that is still active today. Beginning in the early Jurassic, a number of island arcs and continental fragments accreted to the western margin of the North American craton, such that the continental margin has been extended hundreds of kilometers to the west (Ricketts, 2008). The Canadian Cordillera has been divided into 5 morphogeological belts which are aligned parallel to the general tectonic trend. These include, from west to east, the Insular, Coast, Intermontane, Omineca, and Foreland fold belts (Fig. 2.6). Each belt is defined by a characteristic combination of rock types, structural style, and metamorphic grade. For our purposes, the highly deformed, predominantly igneous and metamorphic belts will be grouped here, whereas the moderately deformed, predominantly sedimentary Foreland belt and intermontane basins will be considered in section 2.3.3.

The Insular Belt is located in the southwestern-most corner of the Yukon where it forms the Saint Elias Mountains. The Coast Belt is composed mainly of granitic and metamorphic rocks of the Coast Plutonic Complex. The Intermontane Belt is generally of lower elevation, and comprises an agglomeration of accreted terranes. The Omineca Belt to the west is an uplifted region of mainly metamorphic and granitic rocks, which lies west of the folded and thrust sediments of the Foreland belt, which accumulated on the margin of North America to the east.

The Cordillera is characterised largely by deformed metasedimentary and igneous rocks. While these crystalline rocks typically have higher conductivity than sedimentary rocks (and therefore higher rates of heat loss), there are, however, distinct regions that show great potential for geothermal resources due to high heat flow. Particularly in the Yukon, the Canadian Cordillera hosts numerous volcanic belts and intrusive bodies that formed in relation to orogenic processes (Fig. 2.7). These features have great potential for high temperature geothermal resources; however, limited knowledge on thermal gradients and heat generation impedes accurate assessment, necessitating further investigation (Grasby et al., 2011a).

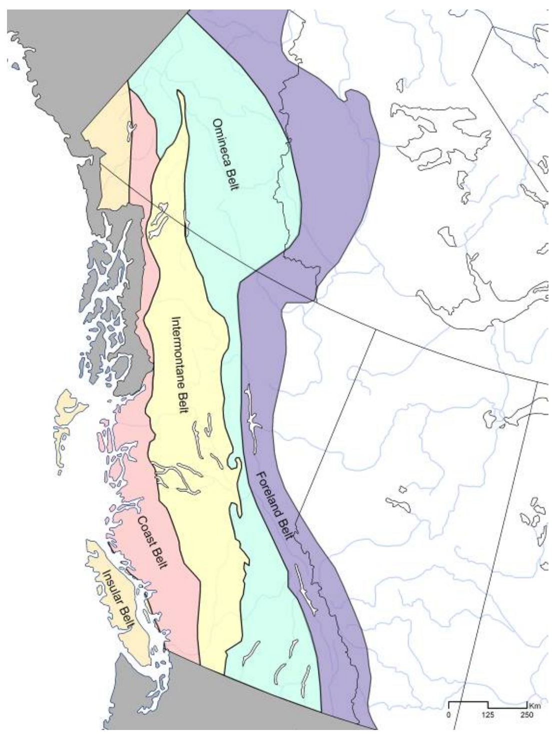

Figure 2.6: Map showing the 5 morphogeological belts of the Canadian Cordillera.

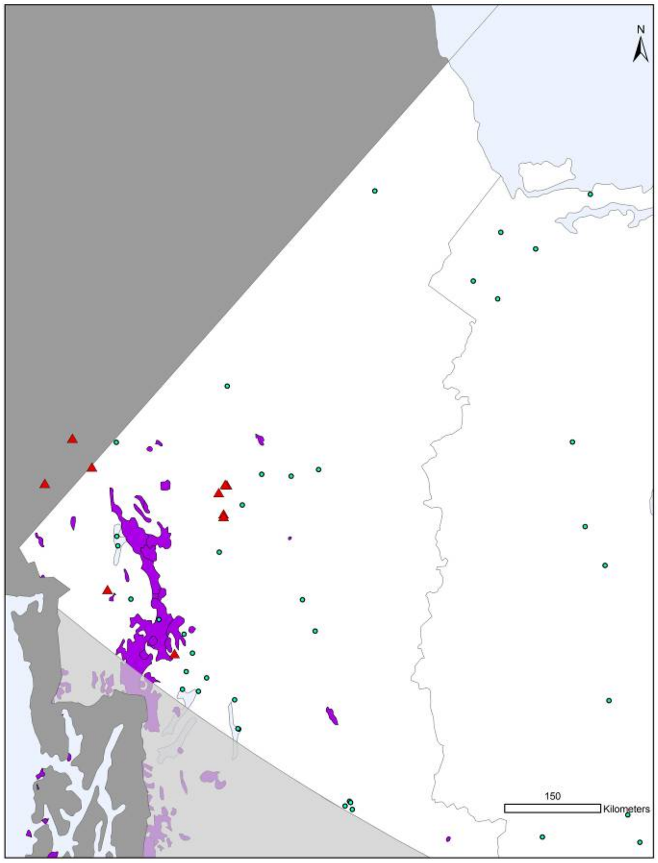

Figure 2.7: Tertiary intrusive rocks (purple) and volcanoes (red triangles) located in Northern Canada. Communities are shown in green.

Volcanism in the Canadian Cordillera has occurred from the onset of orogenesis to recent times, however, only Holocene, Pleistocene, and Pliocene volcanic centres potentially remain hot enough to generate geothermal resources. The two main volcanic provinces in the Yukon are the Northern Cordilleran Volcanic Province, and the Wrangell Volcanic Belt. The Northern Cordilleran Volcanic Province, one of the largest volcanic provinces in western North America, runs roughly north-south through northern British Columbia, Yukon, and Alaska, and contains more than 50 Holocene eruptive centres. The Wrangell Volcanic Belt extends into the southwestern Yukon from Alaska, and hosts several large volcanoes that have been active during the Holocene.

Non-volcanic, igneous intrusive bodies of Tertiary age or younger may also hold potential for the development of hot dry rock geothermal systems due to abundance of radiogenic elements. Previous work has shown that such intrusions in British Columbia may still have high heat generation (Lewis, 1984).

While the porosity and permeability of crystalline rocks is limited or non-existent, the extensive fault systems in the region may act as conduits for fluid flow. Thermal spring systems within the northern Cordillera may indicate the presence of local geothermal anomalies. Hot springs may be used as a tool for exploring geothermal potential in these regions.

2.3.3 Sedimentary Basins

Sedimentary basins often contain porous rock which can host thermal fluids at depth. Together with the low conductivity of sedimentary rocks, these features make sedimentary basins a promising geologic setting to investigate geothermal potential. Sedimentary rocks cover nearly 50% of northern Canada (Morrell et al., 1995); numerous sedimentary basins have been identified, and will be described here for each territory. Only those basins underlying communities (or within 10 km) will be considered.

YUKON

Whitehorse Basin (Teslin, Teslin Post, Tagish, Carcross, Mt. Lorne, Whitehorse, Ibex Valley)

The Whitehorse Basin is a Late Triassic to Early Cretaceous fault-bounded back arc basin which accreted to the North American cratonic margin during the mid-Jurassic (Ricketts, 2008). It is located within the Intermontane belt of the Canadian Cordillera, and covers a 20,000 km^2 area, though some of this area extends into northern British Columbia. It contains up to 5000 meters of sedimentary and volcanic rocks, which have been deformed by tight folds and faults trending in a north-westerly direction. Deformation and igneous intrusions increase to the southwest. Permeable units may be as deep as 3000 m in some areas (Morrell et al., 1995). Potential reservoir rocks have been identified for oil and gas exploration, including Jurassic reef carbonates and Triassic clastic facies.

Dezadeash Basin (Haines Junction)

The Dezadeash Basin is located northeast of the Denali Fault in southwestern Yukon. Together with the Nutzotin Basin, the Dezadeash Basin formed on the eastern margin of the Insular Superterrane as it accreted onto the North American continent (McClelland et al., 1992). It is truncated and offset from the Nutzotin Basin by approximately 370 km by the Denali fault system. The Dezadeash Basin contains sedimentary strata up to 3000 m thick, ranging in age from mid Jurassic to early Cretaceous age (Rickets, 2008). Sandy gravity flow deposits may provide potential reservoirs.

Old Crow Basin (Old Crow)

The Old Crow Basin is a shallow, intermontane basin in northwestern Yukon, covering an area of approximately 75 000 km^2. It contains up to 2 km of non-marine, Tertiary strata which unconformably overlies approximately 4 km of Mesozoic (distal marine shelf deposits) and Paleozoic (marine carbonate shelf deposits) rocks. These older rocks underlying the Old Crow basin and may contain petroleum reservoir units, however, the area remains largely unexplored due to poor petroleum reservoir potential in the Tertiary strata of the Old Crow Basin (Morrell et al., 1995). This is in part due to the absence of strong seals, however, this is less likely to be problematic for the development of hydrothermal systems.

NWT

Mackenzie Corridor (Paulatuk, Fort McPherson, Tsiigehtchic, Colville Lake, Fort Good Hope, Norman Wells, Tulita, Deline, Wrigley, Wha ti, Fort Simpson, Jean Marie River, Fort Providence, Hay River, Hay River Dene, Fort Resolution, Trout Lake, Fort Liard, Nahanni Butte, Fort Smith)

The Mackenzie Corridor is an extensive geographic area encompassing the Mackenzie River drainage system. The region is bound by the metamorphosed belts of the Canadian Cordillera to the west, and the Canadian Shield to the east. It is underlain by a series of depositional basins which essentially form the northern extension of the Western Canadian Sedimentary Basin – a region less commonly known as the Northern Mainland Sedimentary Basin (Morrow, 2006). For our purposes, these individual basins will be considered as one entity.

The Mackenzie Corridor encompasses both the slightly deformed sedimentary strata of the northern foreland belt of the Canadian Cordillera, and the flat-lying sedimentary strata of the interior platform (Hannigan et al., 2011). The northern Mackenzie corridor is underlain by a thick succession of undeformed Proterozoic sedimentary rocks, whereas in southern regions, it is underlain by the Canadian Shield.

The interior platform area comprises a sedimentary wedge that thickens from zero at the eastern margin up to 5-6 km in the west, adjacent to the northern Foreland belt of the Canadian Rockies and the Mackenzie Mountains in the north. Potential reservoir units include basal Cambrian clastic units in the north, Devonian reefal and dolomitized carbonates, and Cretaceous sand units. The depth at which reservoir units are found is variable, with the greatest potential depth along the western margin of the interior platform.

Folded and thrust faulted strata within the Foreland Belt host a number of stratigraphic units which may act as fluid reservoirs. Due to deformation, older units may be exposed at the surface, and conversely, younger units may be found at greater depths than in flat-lying basin settings. Potential reservoir units include a variety of Proterozoic to Cretaceous carbonate and clastic units (Hannigan et al., 2011). Detailed investigation into local stratigraphy and structures is important in the Foreland Belt region of the Mackenzie Corridor, as the distribution and depth of potential reservoir units is highly variable as compared to undeformed basin sediments.

Mackenzie Delta/Beaufort-Mackenzie Basin (Aklavik, Inuvik, Tuktoyaktuk)

The Mackenzie Delta and Tuktoyaktuk Peninsula region of the northwestern NWT is underlain by both the Jurassic to Early Cretaceous Mackenzie Delta and the Late Cretaceous to Recent Beaufort Mackenzie Basin. The area has been extensively explored for petroleum resources, both on and offshore.

The older Mackenzie Delta formed as a result of rifting of the continental margin, and contains a thick accumulation (>5000 m) of shoreface, deltaic, and marine shelf deposits. It is underlain by faulted Paleozoic strata and overlain by the landward margin of the younger Beaufort Mackenzie Basin. Jurassic and Paleozoic sandstones as well as Paleozoic carbonates may be examined as potential permeable reservoirs (Morrell et al., 1995)

The younger Beaufort-Mackenzie Basin represents the southern end of a trough formed in association with the opening of the Arctic Ocean. The Beaufort-Mackenzie Basin is composed of northward-prograding deltaic sediments, which cover an area of ~66,000 km^2, 30% of which is located onshore in the Mackenzie Delta and Tuktoyaktuk Peninsula region. Offshore, basin fill reaches a maximum thickness of 12-16 km; onshore, these sediments are expected to be thinner, but substantially thick for geothermal resource development, as previously drilled petroleum wells extend to depths >3000 m without encountering crystalline basement rocks. The onshore extent of the Beaufort-Mackenzie basin is confined by the Yukon Coastal Plain to the southwest, and the Canadian Shield to the southeast. Thick accumulation of deltaic sandstones are potential reservoirs in onshore regions.

Arctic Continental Terrace Wedge (Sachs Harbour)

The Arctic Continental Terrace Wedge is a relatively young (Cretaceous – Recent) passive margin basin located along the western edge of the Canadian Arctic Islands. It contains thick accumulations of sediment; up to 12 km of marine shelf and ocean basin sediments are known from distal areas. However, where inner shelf sedimentary units are exposed along northeastern Banks Island, thicknesses are likely 2 km or less (Morrell et al., 1995). While this basin remains largely unexplored due to its geographic remoteness and offshore extent, it is thought to contain permeable fluvio-deltaic marine sandstones, which may act as potential reservoirs for thermal fluids if these units are found at sufficient depth.

NUNAVUT

Franklinian Basin (Resolute Bay, Grise Fiord)

The Cambrian to Early Carboniferous Franklinian Basin extends over a wide area across the Canadian Arctic Islands and contains up to 10 km of basin fill. Dominantly carbonate sediments were deposited in a continental margin setting until the late Devonian, when the margin transitioned to a foreland basin setting with the progression of the Ellesmerian Orogeny. This orogenic event eventually led to the uplift and folding of much of the Franklinian Basin.

The community of Resolute Bay is located with the Cornwallis fold belt of the Franklinian Basin on Cornwallis Island. Here, Franklinian strata are composed of marine shelf related carbonates and shales. Grise Fiord does not overly the basin directly, but is located less than 10 km away from Franklinian shallow marine shelf sediments found within the Central Ellesmere fold belt of Ellesmere Island.

Reef and shallow shelf carbonates as well as Devonian clastic wedge sediments may have potential as reservoir units within the Franklinian Basin. Major fault systems related to multiple tectonic events in the region may play a role in circulating deep fluids within the basin.

Hudson Bay Basin (Coral Harbour)

The Hudson Bay Basin is one of the largest Paleozoic sedimentary basins in Canada (Zhang, 2008). Apart from exposures on the mainland in the Hudson Bay region, the northern margin of the Hudson Bay Basin is also exposed onshore over a large area of Southampton Island, and can be found within 10 km of the community of Coral Harbour. The basin consists primarily of shallow marine fill, including carbonates and near shore clastic rocks, with small amounts of evaporite and shales (Norris, 2003). Units outcropping on Southampton Island are Upper Ordovician to Lower Silurian in age or older. The portion of the Hudson Bay Basin exposed on Southampton Island is relatively thin compared to thicknesses in the offshore Hudson Bay region (Norris, 1993), and thus, the depth of potential reservoir units may be limited.

Foxe Basin (Hall Beach, Igloolik)

The Foxe Basin is a wide, shallow (600 m maximum thickness) Paleozoic basin which extends northward from the Hudson Bay Basin. The basin formed as a result of rifting within the interior of the continent, with deposition occurring within the basin during the early Paleozoic (Morrell et al., 1995). The Fox basin contains Cambrian clastics and carbonates which overly Precambrian shield rocks. It outcrops onshore on marginal southwestern Baffin Island, as well as on the northeastern tip of Melville Peninsula of the northern mainland where the communities of Hall Beach and Igloolik are located. Onshore exposure is restricted to the basin margin, and as such, basin thickness in this area may be a limiting factor.

M'Clintock Basin (Cambridge Bay, Gjoa Haven, Taloyoak)

Like the Foxe Basin, the M’Clinton Basin is a widespread lower Paleozoic cratonic basin, though it contains thicker accumulations of carbonate and clastic strata (up to 4500 m) (Harrison, 2001). It is located offshore beneath M’Clintock Channel, and onshore on a number of island, including Victoria Island (Cambridge Bay), King William Island (Gjoa Haven), and portions of the northern mainland margin (within 10 km of Taloyoak). Ordovician and Silurian carbonate reef rocks have the greatest potential for porous reservoir units, and deep, basement rooted faults may provide additional means of deep circulation for thermal fluids.

Eclipse Trough/Lancaster Sound Basin (Pond Inlet)

The Lancaster Sound Basin is a large, dominantly offshore failed rift basin at the northwest end of Baffin Bay. Where related strata outcrops onshore on Bylot Island and proximal to Pond Inlet on northeastern Baffin Island, it is referred to as either Pond Inlet Basin or more commonly as the Eclipse Trough. The Eclipse Trough is an underfilled and deeply eroded basin which developed as a fault-related graben formed during the Late Cretaceous to Early Tertiary rifting episode associated with the Eurekan orogeny (Kerr, 1979). Here, Early Cretaceous to Paleocene strata are underlain by crystalline basement rocks and Mesoproterozoic to Ordovician strata (Harrison et al., 2008). Potential reservoirs include Albian- Cenomanian sandstone units equivalent to the Hassel Formation of the Sverdrup Basin (Morrell et al, 1995). However, the limited thickness of sedimentary fill within the Eclipse Trough may not place these sands sufficiently deep for the development geothermal systems.

Table 2.1 Energy usage in northern Canadian communities

Community Name (2006)	Territory	Latitude	Longitude	Population (Statistics Canada - 2011)	Combined Population for Grouped Service Areas	Principal Energy Source	Total Annual Energy Use, 2011 (MWh)	Per Capita Energy Use (MWh/person)	Annual Residental Energy Use, 2011 (MWh)	Annual General Service Energy Use 2011 (MWh)	Residential + General Service Energy Use	Residential Power Sales ($CAD)	General Power Sales ($CAD)	Combined Power Sales (res+gen)	cost per MWh (res + gen)	per capita cost
Aklavik	NWT	68.236565	-135.062430	633	-	diesel generators	3019	4.8	1449	1511	2960	$880,000	$931,000	$1,811,000	$611.82	$2,860.98
Colville Lake	NWT	66.998499	-125.998407	149	-	diesel generators	406	2.7	175	223	398	$291,000	$419,000	$710,000	$1,783.92	$4,765.10
Dettah	NWT	62.415629	-114.303846	210	-	Snare hydro grid/diesel back-up	927	4.4	578	334	912	$169,000	$123,000	$292,000	$320.18	$1,390.48
Deline	NWT	65.214438	-123.434375	472	-	diesel generators	2426	5.1	1157	1234	2391	$853,000	$862,000	$1,715,000	$717.27	$3,633.47
Enterprise	NWT	60.567362	-116.242272	87	-	Taltson hydro grid/diesel back-up	included in Hay River value	-	-	-	-	-	-	-	-	-
Fort Good Hope	NWT	66.260969	-128.538788	515	-	diesel generators	2609	5.1	1214	1345	2559	$800,000	$822,000	$1,622,000	$633.84	$3,149.51
Fort Liard	NWT	60.256337	-123.376694	536	-	diesel generators	2663	5.0	1039	1554	2593	$611,000	$856,000	$1,467,000	$565.75	$2,736.94
Fort McPherson	NWT	67.432727	-134.821687	792	-	diesel generators	3289	4.2	1619	1605	3224	$1,155,000	$1,082,000	$2,237,000	$693.86	$2,824.49
Fort Providence	NWT	61.424167	-117.608506	734	-	diesel generators	3002	4.1	-	-	-	-	-	-	-	-
Fort Resolution	NWT	61.032546	-113.663783	474	-	Taltson hydro grid/diesel back-up	2712	5.7	1518	1117	2635	$334,000	$238,000	$572,000	$217.08	$1,206.75
Fort Simpson	NWT	61.803941	-121.320528	1238	-	diesel generators	6787	5.5	2772	3905	6677	$1,719,000	$2,227,000	$3,946,000	$590.98	$3,187.40
Fort Smith	NWT	60.020356	-112.074257	2093	-	Taltson hydro grid/diesel back-up	21939	10.5	10251	11428	21679	$1,844,000	$1,744,000	$3,588,000	$165.51	$1,714.29
Hay River	NWT	60.732867	-115.925636	3606	3985	Taltson hydro grid/diesel back-up	30119	7.6	-	-	-	-	-	-	-	-
Hay River Dene	NWT	60.789937	-115.688524	292	-	Taltson hydro grid/diesel back-up	included in Hay River value	-	-	-	-	-	-	-	-	-
Ulukhaktok	NWT	70.730332	-117.678674	402	-	diesel generators	1989	4.9	861	1105	1966	$586,000	$650,000	$1,236,000	$628.69	$3,074.63
Inuvik	NWT	68.332114	-133.578985	3463	-	natural gas (locally derived)	27855	8.0	8313	19413	27726	$4,603,000	$9,444,000	$14,047,000	$506.64	$4,056.31
Jean Marie River	NWT	61.509152	-120.652460	64	-	diesel generators	226	3.5	100	115	215	$93,000	$190,000	$283,000	$1,316.28	$4,421.88
Kakisa	NWT	60.925148	-117.323989	45	-	diesel generators	393	8.7	-	-	-	-	-	-	-	-
Lutselk'e	NWT	62.384428	-110.686111	295	-	diesel generators	1410	4.8	716	671	1387	$523,000	$465,000	$988,000	$712.33	$3,349.15
Nahanni Butte	NWT	60.998398	-123.386321	102	-	diesel generators	429	4.2	201	216	417	$204,000	$368,000	$572,000	$1,371.70	$5,607.84
Norman Wells	NWT	65.284071	-126.687235	727	-	natural gas (locally derived)	8679	11.9	2755	5843	8598	$1,147,000	$2,160,000	$3,307,000	$384.62	$4,548.83
Paulatuk	NWT	69.325307	-123.984982	313	-	diesel generators	1434	4.6	590	815	1405	$637,000	$864,000	$1,501,000	$1,068.33	$4,795.53
Gameti	NWT	64.118216	-117.303708	253	-	diesel generators	956	3.8	477	460	937	$453,000	$615,000	$1,068,000	$1,139.81	$4,221.34
Behchoko	NWT	62.828295	-115.969356	1926	-	Snare hydro grid/diesel back-up	7183	3.7	4015	3078	7093	$1,044,000	$1,018,000	$2,062,000	$290.71	$1,070.61
Sachs Harbour	NWT	72.033057	-125.270535	112	-	diesel generators	836	7.5	298	510	808	$386,000	$637,000	$1,023,000	$1,266.09	$9,133.93
Wekweeti	NWT	64.201331	-114.189798	141	-	diesel generators	604	4.3	-	-	-	-	-	-	-	-
Trout Lake	NWT	60.423645	-121.158142	92	-	diesel generators	442	4.8	-	-	-	-	-	-	-	-
Tsiigehtchic	NWT	67.425596	-133.680965	143	-	diesel generators	685	4.8	291	373	664	$285,000	$343,000	$628,000	$945.78	$4,391.61
Tuktoyaktuk	NWT	69.428864	-133.016282	854	-	diesel generators	3855	4.5	2049	1734	3783	$1,238,000	$1,066,000	$2,304,000	$609.04	$2,697.89
Tulita	NWT	64.923096	-125.455337	478	-	diesel generators	2228	4.7	1134	1054	2188	$915,000	$864,000	$1,779,000	$813.07	$3,721.76
Wha-ti	NWT	63.159213	-117.233723	492	-	diesel generators	1570	3.2	893	658	1551	$647,000	$510,000	$1,157,000	$745.97	$2,351.63
Wrigley	NWT	63.196239	-123.346571	133	-	diesel generators	600	4.5	250	325	575	$232,000	$398,000	$630,000	$1,095.65	$4,736.84
Yellowknife	NWT	62.470569	-114.421231	19234	-	Snare hydro grid/diesel back-up	160012	8.3	-	-	-	-	-	-	-	-
Arctic Bay	Nunavut	73.03572	-85.188844	823	-	diesel generators	2725	3.3	-	-	-	-	-	-	-	-
Arviat	Nunavut	61.099443	-94.169719	2318	-	diesel generators	7398	3.2	-	-	-	-	-	-	-	-
Baker Lake	Nunavut	64.327032	-96.028323	1872	-	diesel generators	7642	4.1	911		911	-	-	-	-	-
Umingmaktok	Nunavut	67.70535	-107.843991	5	-	diesel generators	**n/a**	-	-	-	-	-	-	-	-	-
Qikiqtarjuaq	Nunavut	67.544192	-63.904129	520	-	diesel generators	2296	4.4	-	-	-	-	-	-	-	-
Cambridge Bay	Nunavut	69.150061	-105.186022	1608	-	diesel generators	8448	5.3	-	-	-	-	-	-	-	-
Cape Dorset	Nunavut	64.223745	-76.540525	1363	-	diesel generators	5493	4.0	-	-	-	-	-	-	-	-
Chesterfield Inlet	Nunavut	63.309842	-90.827649	313	-	diesel generators	1665	5.3	-	-	-	-	-	-	-	-
Clyde River	Nunavut	70.46335	-68.482395	934	-	diesel generators	3167	3.4	-	-	-	-	-	-	-	-
Coral Harbour	Nunavut	64.173996	-83.247774	834	-	diesel generators	2914	3.5	-	-	-	-	-	-	-	-
Gjoa Haven	Nunavut	68.644753	-95.891213	1279	-	diesel generators	4639	3.6	-	-	-	-	-	-	-	-
Grise Fiord	Nunavut	76.492478	-82.754343	130	-	diesel generators	995	7.7	-	-	-	-	-	-	-	-
Hall Beach	Nunavut	68.775134	-81.263070	546	-	diesel generators	2571	4.7	-	-	-	-	-	-	-	-

Igloolik	Nunavut	69.402926	-81.686511	1454	-	diesel generators	5390	3.7	-	-	-	-	-	-	-	-
Iqaluit	Nunavut	63.760166	-68.510290	6699	-	diesel generators	50483	7.5	-	-	-	-	-	-	-	-
Kimmirut	Nunavut	62.849028	-69.874180	455	-	diesel generators	1856	4.1	-	-	-	-	-	-	-	-
Kugluktuk	Nunavut	67.832205	-115.443926	1450	-	diesel generators	5071	3.5	-	-	-	-	-	-	-	-
Nanisivik	Nunavut	73.004287	-84.545387	10	-	diesel generators	**n/a**	-	-	-	-	-	-	-	-	-
Pangnirtung	Nunavut	66.143466	-65.682225	1425	-	diesel generators	6013	4.2	-	-	-	-	-	-	-	-
Kugaaruk	Nunavut	68.530127	-89.809420	771	-	diesel generators	2306	3.0	-	-	-	-	-	-	-	-
Pond Inlet	Nunavut	72.68085	-77.750514	1549	-	diesel generators	5365	3.5	-	-	-	-	-	-	-	-
Rankin Inlet	Nunavut	62.812894	-92.125325	2266	-	diesel generators	14785	6.5	-	-	-	-	-	-	-	-
Repulse Bay	Nunavut	66.562624	-86.313253	945	-	diesel generators	2783	2.9	-	-	-	-	-	-	-	-
Resolute	Nunavut	74.719052	-94.879722	214	-	diesel generators	3379	15.8	-	-	-	-	-	-	-	-
Sanikiluaq	Nunavut	56.529814	-79.220922	812	-	diesel generators	3145	3.9	-	-	-	-	-	-	-	-
Taloyoak	Nunavut	69.553371	-93.505000	899	-	diesel generators	3145	3.5	-	-	-	-	-	-	-	-
Whale Cove	Nunavut	62.323752	-92.839521	407	-	diesel generators	1530	3.8	-	-	-	-	-	-	-	-
Beaver Creek	Yukon	62.379897	-140.893186	103	-	diesel generators	1865	18.1	-	-	-	-	-	-	-	-
Burwash Landing	Yukon	61.351096	-139.013672	95	150	diesel generators	1609	10.7	-	-	-	-	-	-	-	-
Carcross (including Carcross 4)	Yukon	60.180167	-134.712711	342	-	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	3257	9.5	-	-	-	-	-	-	-	-
Carmacks	Yukon	62.092856	-136.267271	503	-	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	5041	10.0	-	-	-	-	-	-	-	-
Dawson	Yukon	64.045084	-139.372648	1319	-	Mayo hydro grid with diesel back-up	16479	12.5	7009	9332	16341	-	-	-	-	-
Faro	Yukon	62.237715	-133.315338	344	-	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	9724	28.3	2020	7609	9629	-	-	-	-	-
Haines Junction	Yukon	60.771016	-137.508335	593	-	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	6866	11.6	-	-	-	-	-	-	-	-
Ibex Valley	Yukon	60.836567	-135.629595	346	-	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	included in Whitehorse value	-	-	-	-	-	-	-	-	-
Mayo	Yukon	63.596116	-135.895450	226	-	Mayo hydro grid/diesel back-up	18200	80.5	2817	3884	6701	-	-	-	-	-
Mt. Lorne	Yukon	60.418403	-134.927491	408	-	diesel generators	included in Whitehorse value	-	-	-	-	-	-	-	-	-
Old Crow	Yukon	67.578699	-139.840773	245	-	diesel generators	1971	8.0	-	-	-	-	-	-	-	-
Pelly Crossing	Yukon	62.836345	-136.587928	336	-	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	2523	7.5	-	-	-	-	-	-	-	-
Ross River	Yukon	61.967009	-132.448256	352	-	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	2690	7.6	-	-	-	-	-	-	-	-
Stewart Crossing	Yukon	63.360795	-136.694359	25	-	Mayo hydro grid with diesel back-up	413	16.5	-	-	-	-	-	-	-	-
Tagish	Yukon	60.289916	-134.302857	391	-	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	2018	5.2	-	-	-	-	-	-	-	-
Teslin	Yukon	60.172724	-132.715539	122	260	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	4366	16.8	-	-	-	-	-	-	-	-
Teslin Post	Yukon	60.172004	-132.740590	138	-	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	included in Teslin value	-	-	-	-	-	-	-	-	-
Upper Liard	Yukon	60.053501	-128.919887	132	142	diesel generators	814	5.7	-	-	-	-	-	-	-	-
Watson Lake	Yukon	60.061916	-128.689893	802	-	diesel generators	11831	14.8	-	-	-	-	-	-	-	-
Whitehorse	Yukon	60.688273	-135.094819	23276	24030	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	249911	10.4	-	-	-	-	-	-	-	-
Marsh Lake	Yukon	60.516667	-134.333056	619	-	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	4300	6.9	-	-	-	-	-	-	-	-
Keno	Yukon	63.909167	-135.304167	28	-	Mayo hydro grid with diesel back-up	351	12.5	-	-	-	-	-	-	-	-
Johnson's Crossing	Yukon	60.489425	-133.294536	15	-	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	87	5.8	39	49	88	-	-	-	-	-
Destruction Bay	Yukon	61.254167	-138.806667	55	-	diesel generators at Burwash Landing	included in Burwash Landing value	-	-	-	-	-	-	-	-	-
Champagne	Yukon	60.785833	-136.480556	24	-	Whitehorse-Aishihik-Faro hydro grid/diesel back-up	745	31.0	557	183	740	-	-	-	-	-
Two and One-Half Mile Village	Yukon	60.143227	-128.881218	0	-	diesel generators	included in Upper Liard value	-	-	-	-	-	-	-	-	-
Two Mile Village	Yukon	60.134763	-128.835482	10	-	diesel generators	included in Upper Liard value	-	-	-	-	-	-	-	-	-

3. METHODS

3.1 Data Sources

Community and Energy Use Data

Population data was obtained from the Statistics Canada 2011 Population Census (www.statcan.gc.ca).

Power usage data (total power; MWh) for 2011 was provided by Northwest Territories Power Corporation, Northland Utilities (ATCO), Yukon Electrical Company (ATCO), Yukon Energy Corporation, and Qulliq Energy Corporation (Government of Nunavut). In some cases, individual communities are grouped under a single service area (see Table 2.1); in these cases, population values were also combined in order to estimate per-capita energy usage (MWh/person).

Revenue data ($CAD) was only available for communities serviced by Northwest Territories Power Corporation. This information was used to calculate the sum of "residential" and "general sales" revenue to approximate energy used by community members - excluding industrial activity. The calculated sum of residential and general sales revenue ($CAD) was divided by the sum of residential and general sales power use (MWh) in order to obtain cost per mega watt hour. These values were also divided by population numbers to derive per-capita costs ($CAD/MWh/person).

Well Log Analysis

Digital well log data for northern petroleum wells was obtained by the GSC from various private vendors. One hundred and fifty well log analyses were performed by Y. Lui of SoftMirrors Ltd. based on a selection of digital well logs (LAS format). See section 3.4.1 for well selection methods.

Geothermal Data

Measurement of temperature profiles with depth is very expensive given the initial drilling costs and has rarely been conducted for the purpose of geothermal investigation in Canada. However, there are numerous sources of temperature data that can be used to aid resource evaluation, particularly temperature measurements recorded during petroleum well drilling and development. During drilling several tests are conducted (e.g. drill stem test – or DST) that includes measurement of formation fluid temperatures. Here a section of the well is packed off during drilling and fluids are produced to surface from a defined depth range. Temperature recorded during these tests often provide a reasonable approximation of true temperatures at the depth the fluids are produced from.

During geophysical logging of a well the maximum temperature reached when the logging tool reaches the bottom of the hole is recorded. These temperatures are often lower than true temperatures at depth given that the drilling process disrupts the temperature profile through the circulation of drilling fluids. However there are methods available for temperature data to be corrected back to a 'true' formation temperature (Sec 3.2). Producing oil and gas wells also report production temperatures that more likely reflect true sub-surface temperatures. Data collected as part of the Geothermal Energy Program (Jessop, 2008a,b), include detailed and accurate depth temperature profiles. Additional unpublished data from industry sources was also used.

Data derived from petroleum wells in the Canadian Territories is held by the National Energy Board. Most data are found in paper copy reports. Geothermal data has been extracted and released in digital file reports for the Arctic Islands and Beaufort regions (Grasby et al., 2011b; Chen et al., 2010; Hu et al., 2010). Further release of reports for the Yukon and NWT are pending (Grasby et al. in prep).

3.2 Temperature Corrections

Harrison et al. (1983) developed calibration methods for BHT data, using mostly drill stem temperature (DST) measurements. Gallardo and Blackwell (1999) also had success comparing corrected BHT data using their equation for thermal reconstructions based on heat flow and conductivity modeling. The following BHT correction equation from Harrison et al. (1983) was used in this study:

$$T_{cf} = -16.5 + 0.09*z - (2.35*10^{6})z^{2}$$

Z is the depth in meters. The temperature correction values (T_{cf}) are then added to the original BHT values. The Harrison correction still maintains a bias related to depth/gradient/temperature differences, therefore a secondary correction (Blackwell and Richards, 2004) that is a function of the BHT well gradient was also applied.

A comparison of corrected bottom hole temperatures (BHT) vs. drill stem test temperatures (DST) for the areas of high heat flow, in southwestern NWT, shows that independent data sources (DST temperatures and BHTs) give comparable results (Fig. 3.1). There are some deep DST values which are very low (<30 ^{o}C). These are considered bad readings likely related to very low flow rates during the DST tests. On the other hand we observed several very high DST temperatures (> 150 ^{o}C) recorded at depth ranges of 2.5 to 3.0 km. These are confirmed by deeper BHTs from 3.1 to 3.2 km depths. While these represent very good temperatures for geothermal energy potential, such isolated high values need farther analysis when mapping temperature–depth tends averaged over larger areas.

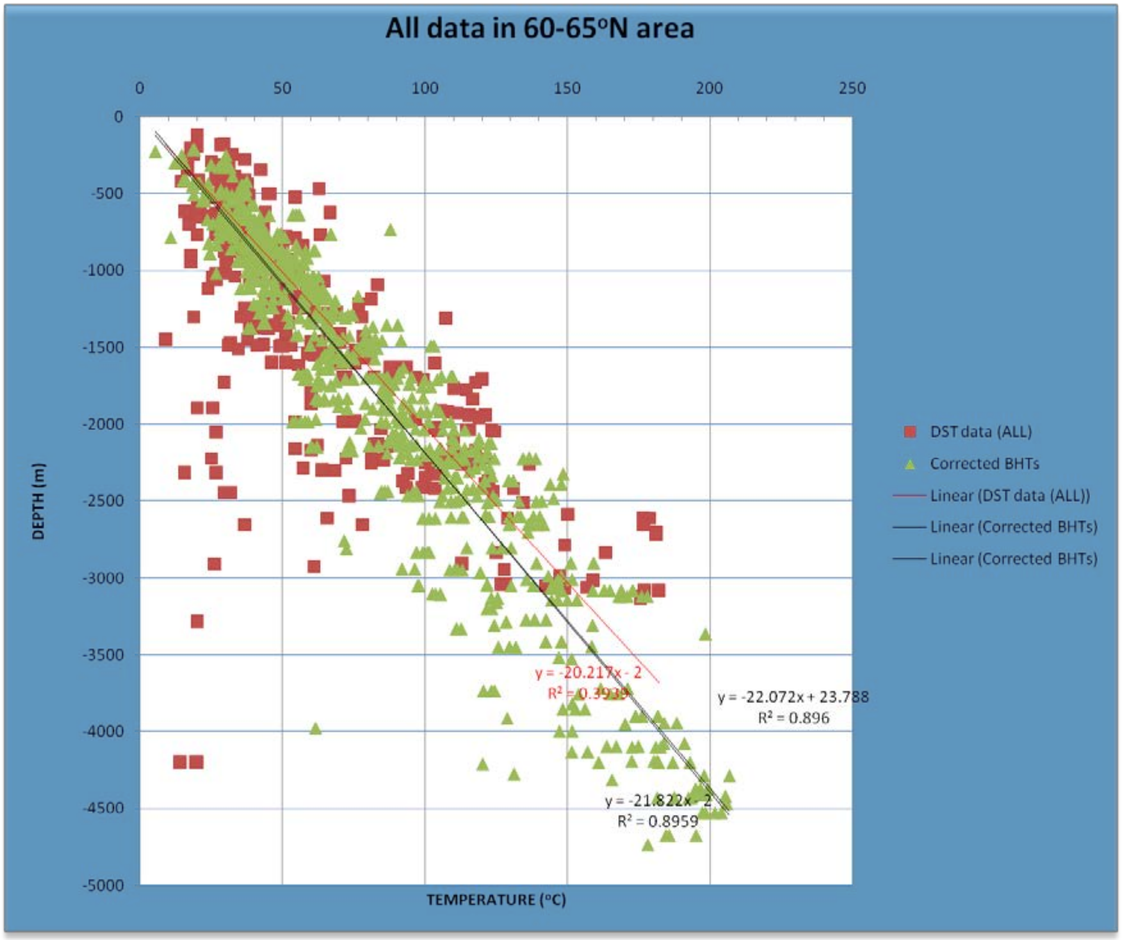

Figure 3.1. Plot showing a comparison of corrected BHTs and DST temperatures versus depth for the southern NWT. Results indicate that both data sources show comparable geothermal gradients.

3.3 Reservoir Assessment

Geothermal developments can be installed in any geological environment as everywhere temperature will increase with depth. The cost of drilling to a desired temperature, which increases exponentially with drilling depth, is a main constraint, however. Given the higher heat flow and lower thermal conductivity of sedimentary basins, they are the primary target areas for geothermal development in the north. As such the reservoir assessment was focused on analyses of sedimentary basins (Fig. 3.2).

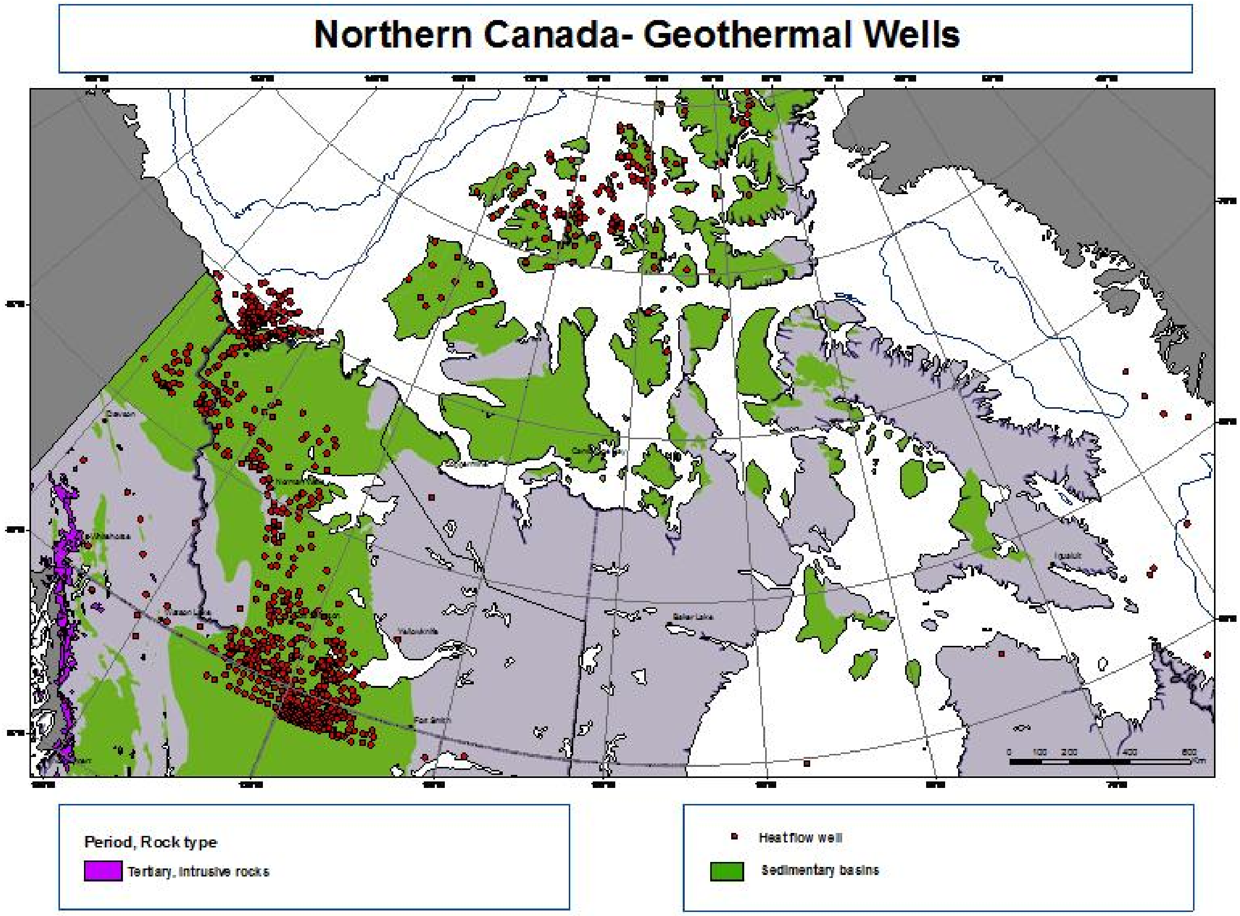

Figure 3.2. A map showing regions of northern Canada underlain by sedimentary basins along with locations of available geothermal measurements from wells.

3.3.1 Well Selection

In order to assess the availability of potential thermal fluid reservoir units in proximity to northern communities, 150 digital well logs were selected for well log analysis.

Wells were chosen according to a hierarchy of criteria. As mentioned in section 2.4, the location of pre-existing wells is restricted to areas of hydrocarbon exploration. For this reason, well log analyses were possible predominantly in the Mackenzie corridor and Beaufort-Mackenzie delta areas (with a few exceptions).

ArcMap 9.3 was used to identify and prioritize suitable wells. Firstly, wells with available gamma ray and porosity logs were isolated. Secondly, wells deeper than 1000 m were selected, as deep reservoir units may have the greatest geothermal potential (either direct heat and/or power generation). Exception was made only along shallow basin margins in areas where heat flow is high (south-eastern margin of the Mackenzie Corridor, NWT). In this case, wells less than <1000 m were selected for the purpose of assessing heat exchange potential. Thirdly, wells were selected based on their proximity to communities. This was accomplished using buffers of 25, 50 and 100 km, with preference given to wells in closest proximity to the community. Lastly, candidate wells underwent a final selection by visual inspection; ensuring selected wells were reasonably spaced.

4. GEOTHERMAL RESOURCES

A series of depth-temperature maps were produced to illustrate the spatial distribution of geothermal resource potential in northern Canada, as a function of depth to resource. While no individual map provides a sense of true geothermal resource potential, the maps are utilized for the broader assessment of candidate communities where the development of geothermal energy resources is most likely to support local energy supply.

4.1 Permafrost Thickness

In Northern Canada, the depth of permafrost is an important constraint to consider when calculating the depth to a desired temperature. Ground temperatures are at or below 0 °C within the permafrost zone. This has the affect of suppressing the normal geothermal gradient, requiring greater drilling depths in regions of thick permafrost. As an example, a temperature profile through permafrost is provided for the Mallik well drilled on Richards Island of the Mackenzie Delta (Fig. 4.1). Here the depth of permafrost is determined where ground temperature reaches 0 °C, at >600 m depth; below this, geothermal gradients resume a "normal" profile of temperature increase with depth. This example illustrates that the depth of a geothermal resource is effectively suppressed by the thickness of this overlying permafrost zone. A regional map of permafrost thickness (Fig. 4.2) shows that permafrost is thickest in northern Canada, where the 0 °C isotherm is depressed to depths up to 900 m, while in the southern territories the 0 °C isotherm is near surface where permafrost becomes discontinuous.

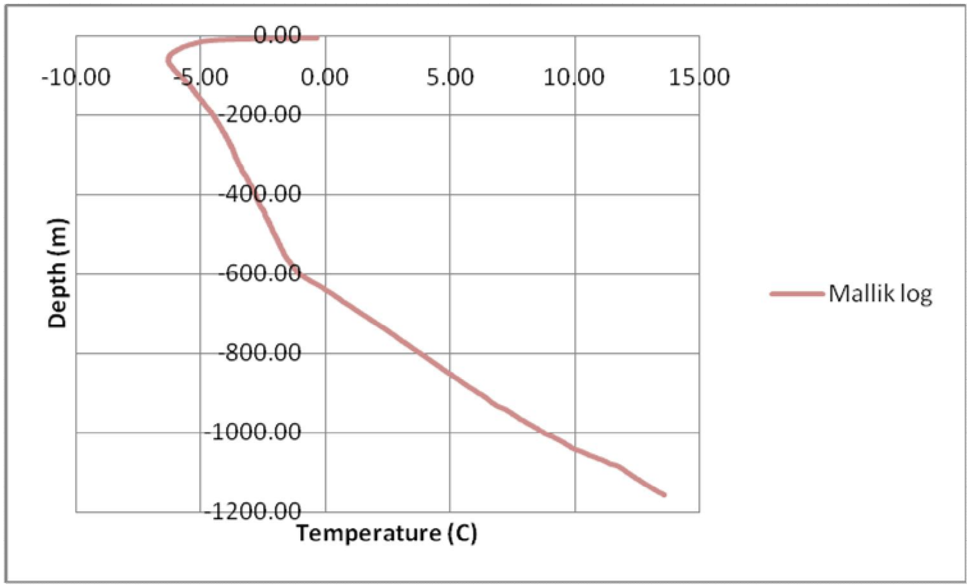

Figure 4.1. Example temperature gradient through region of thick permafrost, derived from a temperature log measured in the GSC Mallik gas hydrate research well in the McKenzie Delta. Note that the 0 °C boundary is depressed to >600 m due to permafrost conditions.

4.2 Heat Flow

The Canadian geothermal database was used to map regional variation in heat flow in northern Canada. The distribution of heat flow data is uneven as large parts of the Canadian Shield do not have any heat flow determinations (Fig 2.3). The interpolation between distant points creates some artifacts, such as the apparent heat flow anomaly in the shield area trending north- west. This is due to data extrapolation from the high heat flow zone in southwestern NWT. In general, the lack of heat flow measurements in the shield area greatly limits knowledge of geothermal potential in that region. However, it is reasonable to assume, given the age of the rocks and high thermal conductivity (K>2.5 W/m K), that heat flow in the shield will be < 50 mW/m^2. This estimation of heat flow would in turn result in estimated geothermal gradients for the shield area of <20 °C/km, implying that most of the shield region is unsuitable for geothermal development.

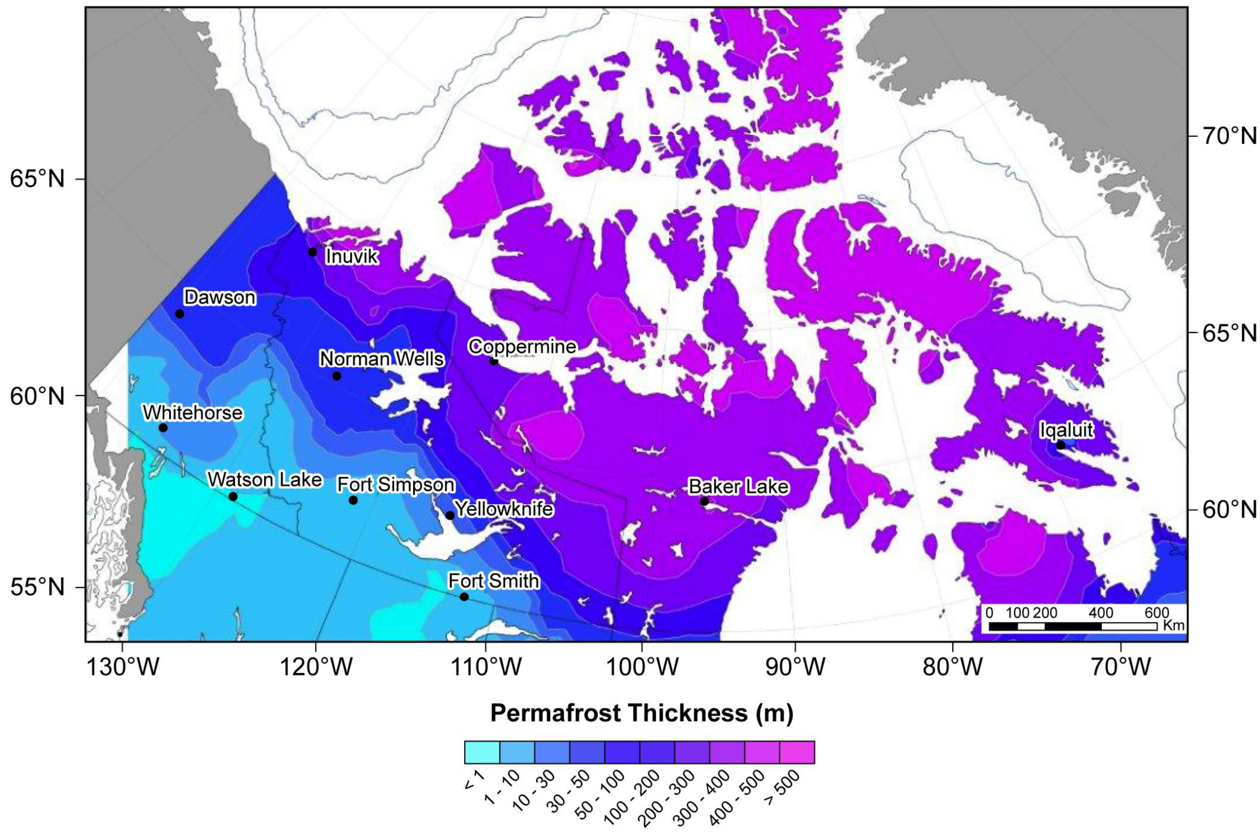

Figure 4.2 Map showing spatial variability in permafrost thickness in northern Canada.

Figure 4.3 shows that higher heat flow areas (>70 mW/m^2) occur in the southwestern part of the NWT (mainly in regions with sedimentary basins) and in the southern part of Yukon Cordillera. In general the northern half of the Mackenzie corridor and northern Yukon has heat flow generally less than 70 mW/m^2. However, some localized areas of higher heat flow do occur. This includes the Norman wells area, NWT, and some areas in the Richards Mountains along the Yukon-NWT border.

4.4 Depth-Temperature maps

In order to assess required drilling depths to geothermal resources, a series of depth-temperature maps were constructed. Maps show spatial variation in depths to temperatures of 40, 60, and 80 °C, (relevant to direct heating geothermal projects) as well as 120 to 150 °C (relevant to electrical production and EGS projects). The maps (Figs. 4.4 – 4.8) were constructed based on existing data for depth temperature profiles, along with depth specific measurements derived from petroleum well logs (drill stem test and corrected bottom-hole temperature data). To aid mapping, estimations of temperature-depth trends were made below the depth of existing recorded temperatures, based on calculation from heat flow, thermal conductivity and average heat generation data (see Majorowicz and Grasby 2010a for the detailed description of methods). Temperature–depth profiles were also constrained by the depth of the 0 ^{o}C isotherm, or base of permafrost (Fig. 4.2). Overall, the patterns of temperature at depth are mainly influenced by the variability of heat flow, where higher heat flow areas produce higher geothermal gradients, thereby reducing the depth to a given resource temperature. Depth to the base of permafrost and assumed thermal conductivity values (2.5W/mK for sedimentary vs. 3W/mK for basement rocks) were also important factors however.

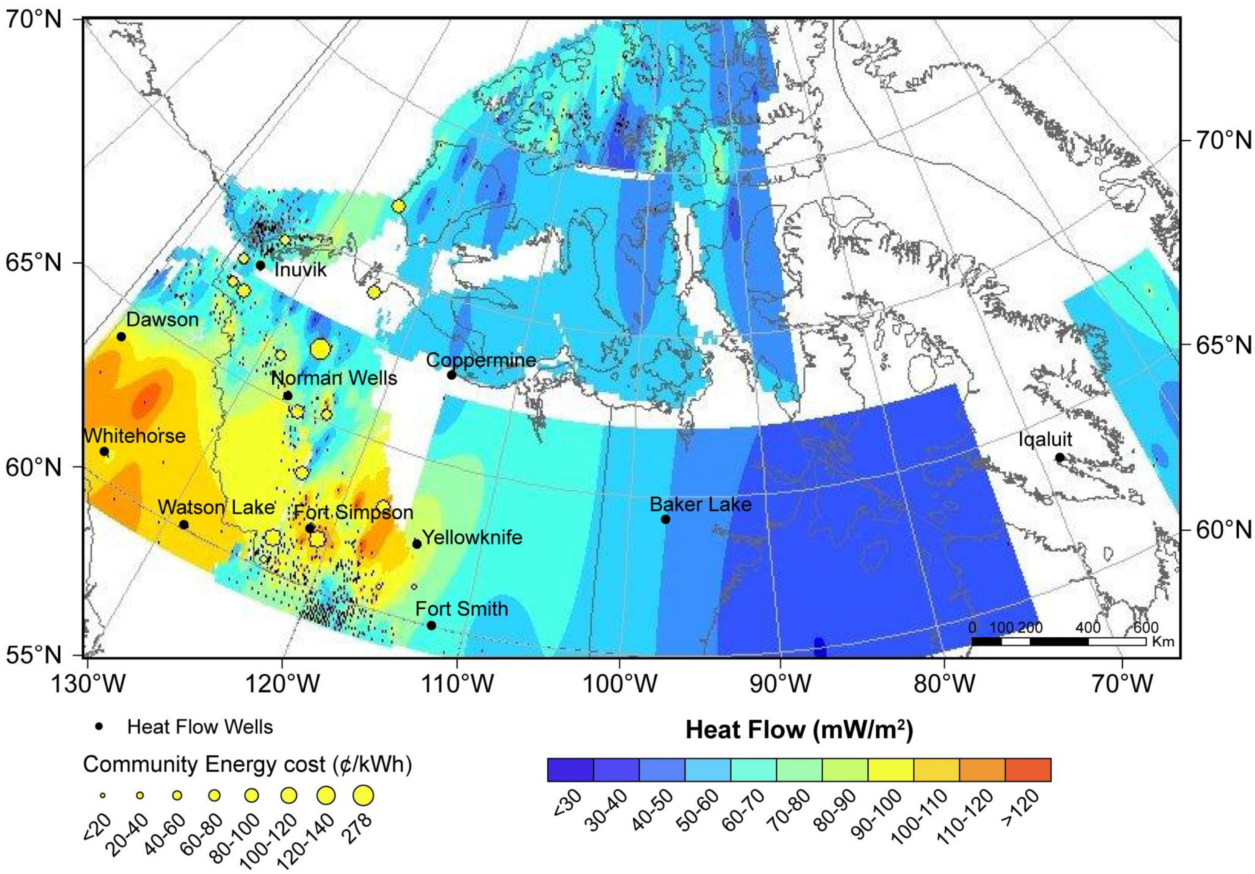

Figure 4.3 Heat flow map of Northern Canada in mW/m^2.

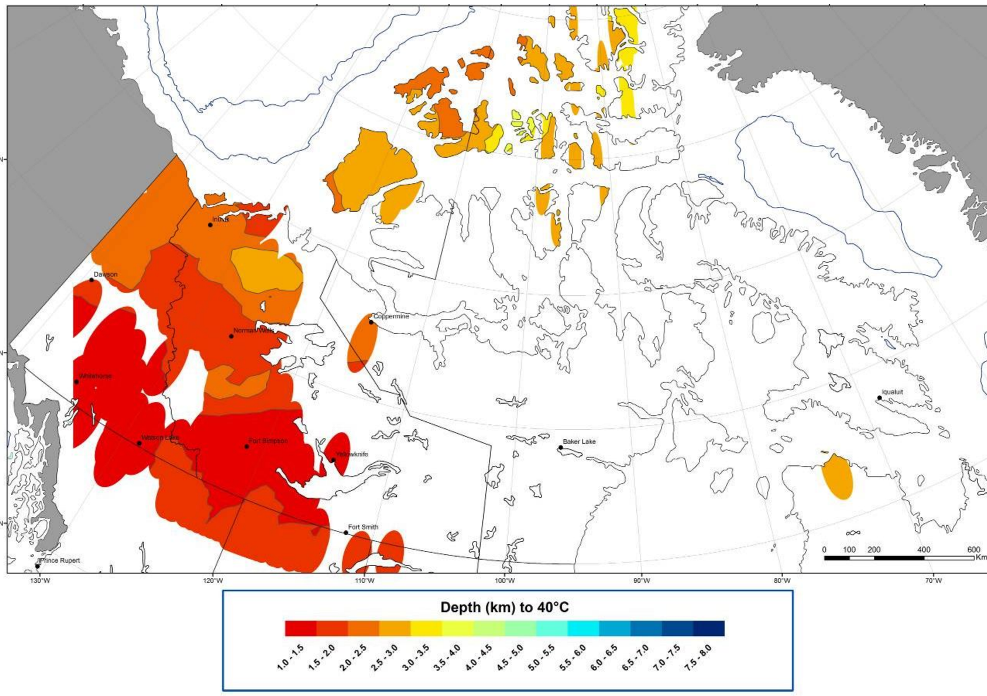

Figure 4.4. Depth to 40 ^{o}C.

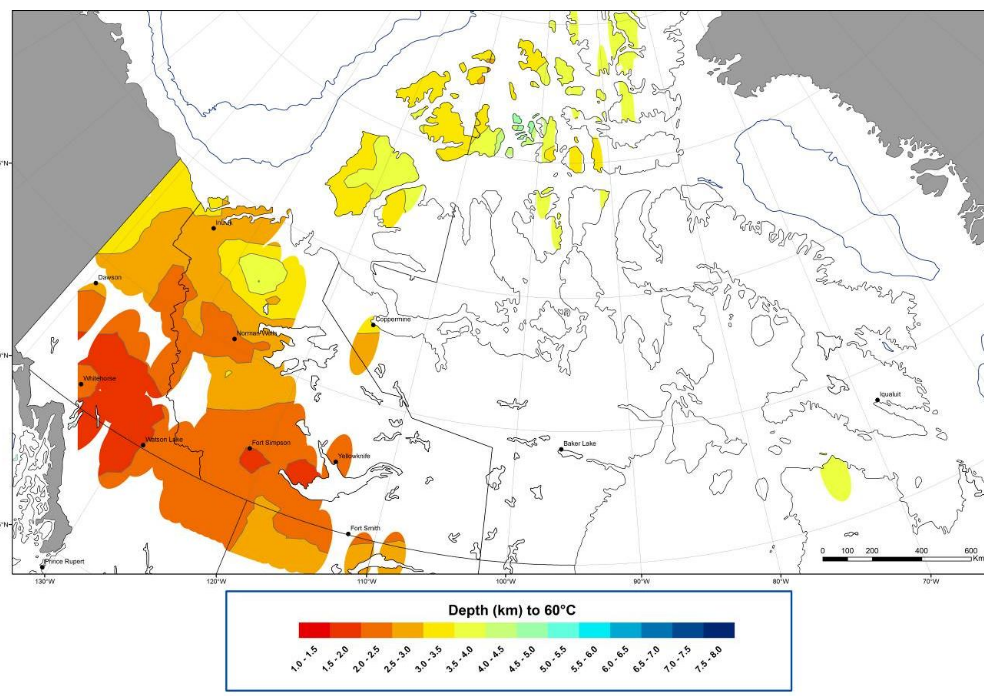

Figure 4.5 Depth to 60 ^{o}C.

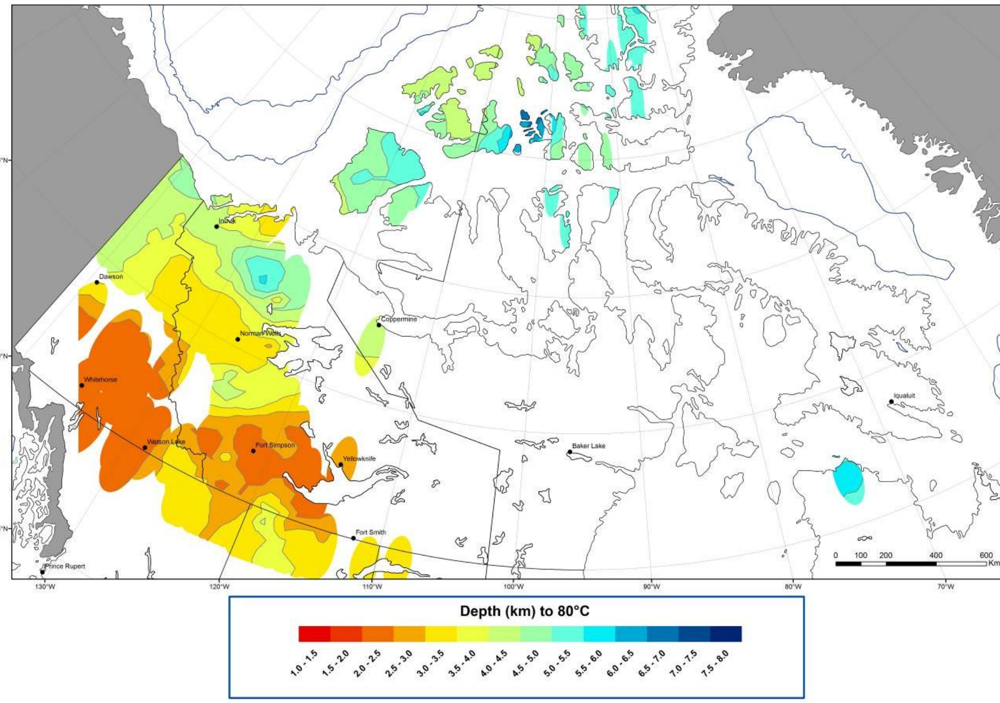

Figure 4.6. Depth to 80 °C.

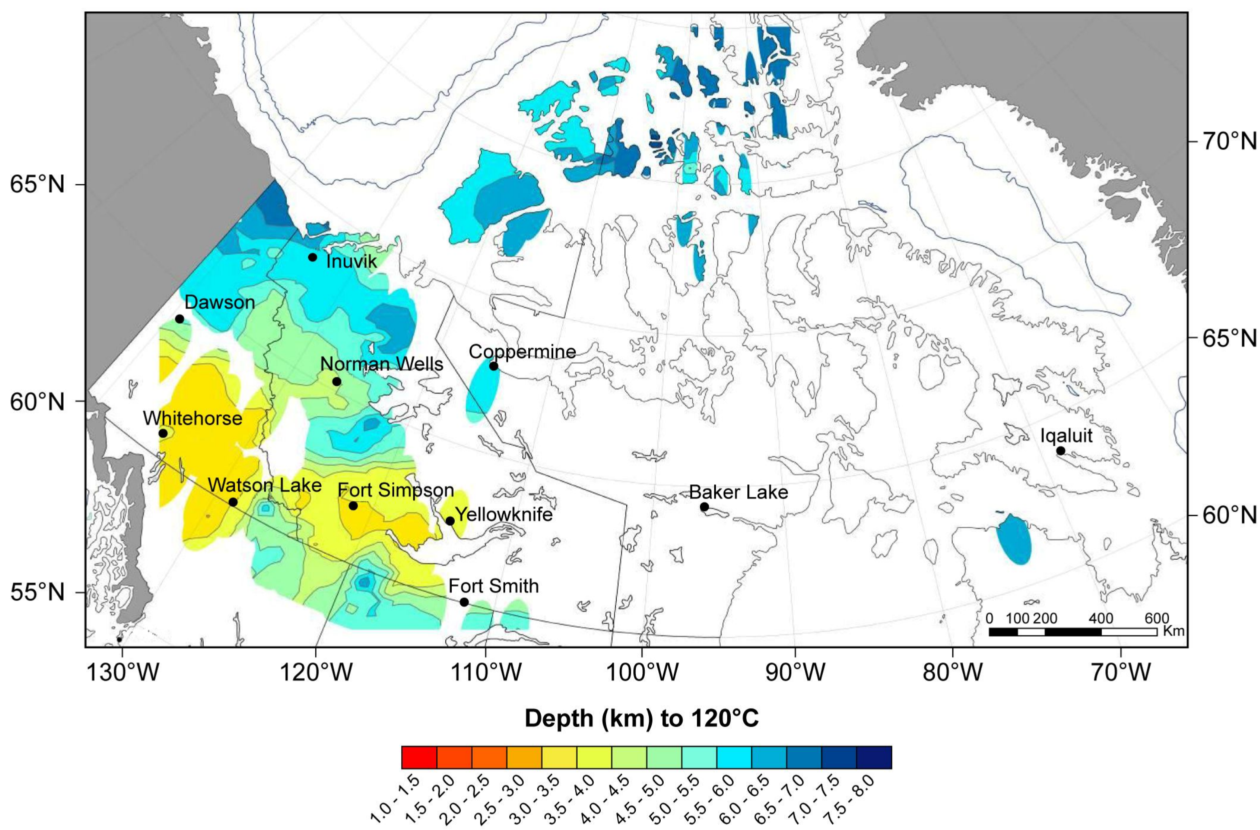

Figure 4.7 Depth to t 120 °C.

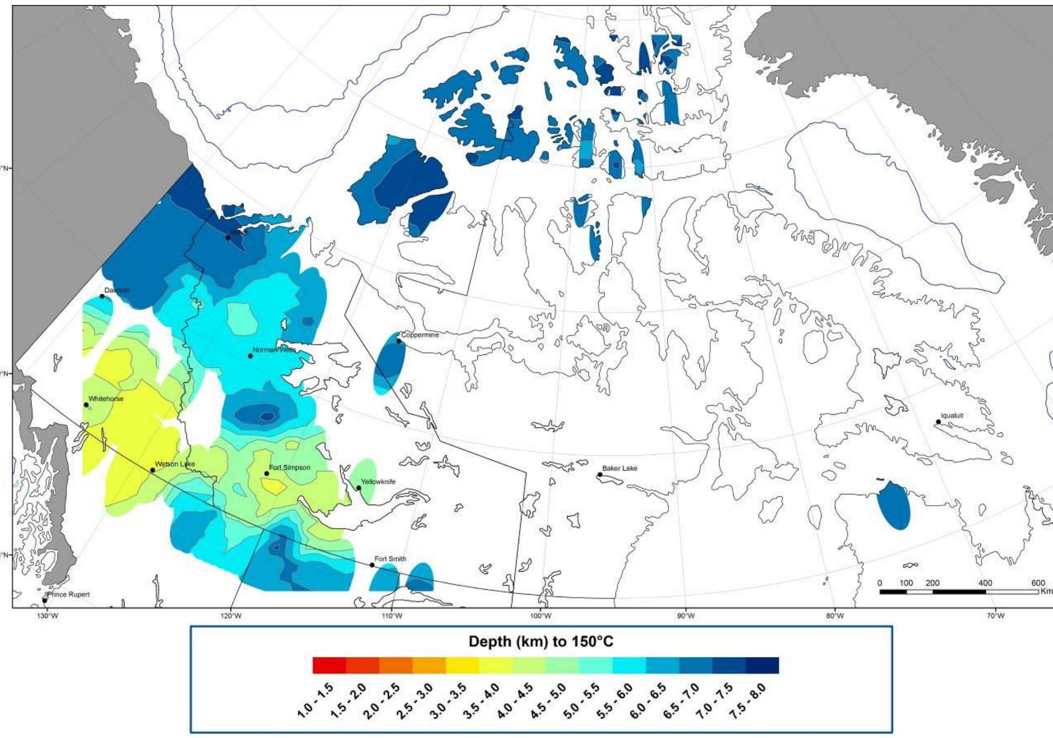

Figure 4.8 Depth to 150 °C.

The depth-temperature maps show that the shallowest drilling depths to a given temperature occur in the southwestern NWT sedimentary basin and the southern Yukon Cordillera. The southern NWT has shallowest depths to potential high temperature resources.

The origin of the thermal anomaly in the southern NWT is not well understood. High temperatures measured in wells south and east of Fort Simpson appear to align with what is known as the Liard Line. This is a deep geological feature that is believed to be a Proterozoic basement structure (Cecile et al., 1997), characterized as a broad zone rather than an abrupt boundary. This structure is thought to have influenced the development of many geological features through the Phanerozoic, including Paleozoic facies boundaries, and indirectly, the Laramide structural evolution of the McKenzie Mountains.

A north–south trending aeromagnetic anomaly also crosses the Fort Simpson area and aligns with thermal anomalies and high heat flow regions further to the south. These geothermal anomalies are coincident with the 1.85 Ga old basement structure known as the Fort Simpson zone. There are no U Th K data to confirm if this zone may have anomalous heat generation, and only a theoretical heat generation of 1.02 $\mu W/m^3$ has been assigned to it by Jessop (1992). However, Burwash and Cummings (1976) and Burwash and Burwash (1989) produced heat generation maps of the Precambrian subsurface in the Western Canadian Sedimentary Basin that show large variations in heat generation, from near 0 up to 9 $\mu W/m^3$. A few data points from the southern NWT are as high as 8 $\mu W/m^3$ and could explain the heat flow of the upper crust in the area.

5. ESTIMATION OF POWER PRODUCTION

The net power output of geothermal plants can be calculated from the geothermal fluid inlet and outlet temperatures, and mass flow rate. For binary power plants, the available thermal flux and related electrical power can be preliminary assessed based on estimated parameters for some specific communities (Table 2.1). These estimates are conducted for both the lower temperature binary system as well as high temperature steam turbine developments.

The available thermal power and related electrical power were assessed on a preliminary basis (for a binary power system conversion rates are given in Tester et al., 2006). This provides a first order estimate of development costs in addition to the potential for electrical and thermal energy available for production. We present here an example system with one production well at 120 °C, which in the southwestern Yukon Cordillera, or in the Mackenzie basin in the Northwest Territories, can be easily reached at depths < 3 km (Fig. 1).

Typical values used (Tester et al, 2006, Majorowicz and Grasby 2010b) are:

1. Water temperature:	120 °C
2. Specific heat capacity of water:	4186 J/(kg °C)
3. Drop off (reinjection) temperature:	50 °C
3. Flow rate range:	30 kg/s

The reinjection temperature of 50 °C is a standard assumed for electrical systems, which is feasible with current technology that uses a binary turbo-system to produce electricity (Tester, 2006; Blackwell et al., 2007).

These parameters give us:

1. Used heat:	296100 J/kg
2. Thermal Power:	9 MWth
3. Electrical power (10% efficiency):	0.9 MWe
4. Electrical power needed to run 2 pumps: (re- injection and producing)	0.65 MWe

5. Net electrical power: 0.25 MWe
6. Yearly energy: 2090 MWh electrical
7. 15 years yearly energy: **32850 MWh**

For the case of a 6 km deep well near maximum current possible drilling depths we would get 5400 MWh electrical yearly from a 150 °C reservoir, and nearly 10,000 kWh for a 200 °C reservoir.

Based on this approach we developed a map (Fig. 5.1) to illustrate the spatial variability of potential available energy yearly (GWh electrical) for northern Canada that would be possible for 6 km depth development based on a doublet well.

5.1 Overnight Cost Estimates

One of the major up front costs in a geothermal project is drilling which needs to be averaged over the lifespan of the project (in this case 15 years). The risk of failure to reach rock suitable for sustaining the large flow rates required (~30 kg/d) are not included in cost calculations we do here. We had though updated to 2010 dollars the drilling-cost function provided in Tester et al. (2006).

Capital costs for surface equipment and facility construction, as outlined in Majorowicz and Grasby (in review), where used to map spatial variability in the cost per kWh electrical for a theoretically geothermal project (Fig. 5.1) targeting a 120 °C resource at the predicted depth to reach that temperature resource (based on depth estimates of Majorowicz and Grasby in review). Results suggest that geothermal energy costs are at potential economical levels for the southwestern part of northern Canada where communities have comparable energy cost per kWh (e.g. Fort Liard is near 50 cents). Not included in this estimate are additional potential economic benefits that can be realized if geothermal energy is also used for direct heating. For example, rather than reinject waters at 50 °C after passing through an ORC (Organic Rankin Cycle) for electrical production, additional heat could be extracted for direct heating, thereby dropping injection waters down to 30 °C.

As another example we examined the case of targeting deep high temperature geothermal energy resources near the limits of feasibly drilling depths of 6 km wells. This suggests the potential for competitive geothermal energy costs (50 c/kWh) with yearly energy production of some 5000 MWh (Fig. 5.2). Such energy production and low cost per kWh can be achieved in most of the Cordillera and southern parts of the NWT. The most economical regions are in the southwestern portion of the study area where electrical energy cost could be as low as 10 to 20 cents/kWh. However, large areas further north are more likely not economical as the amount of energy needed to put into the system (pumping, etc.) would be larger than the energy available.

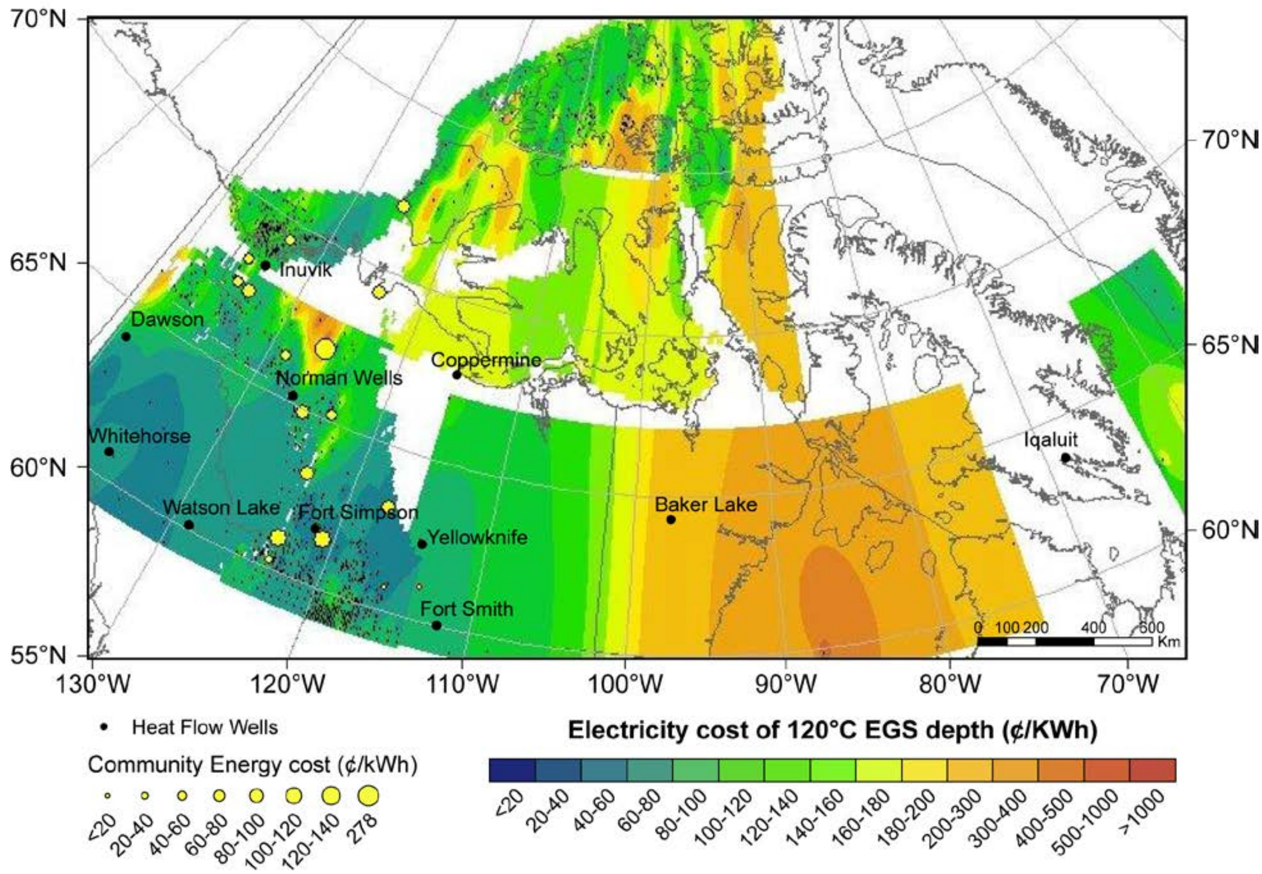

Figure 5.1. Patterns of cost per kWh calculated for modeled EGS system to tap to 120 ^{o}C temperature resource at varying drilling depth (see Fig.1) for the Northern Canada.

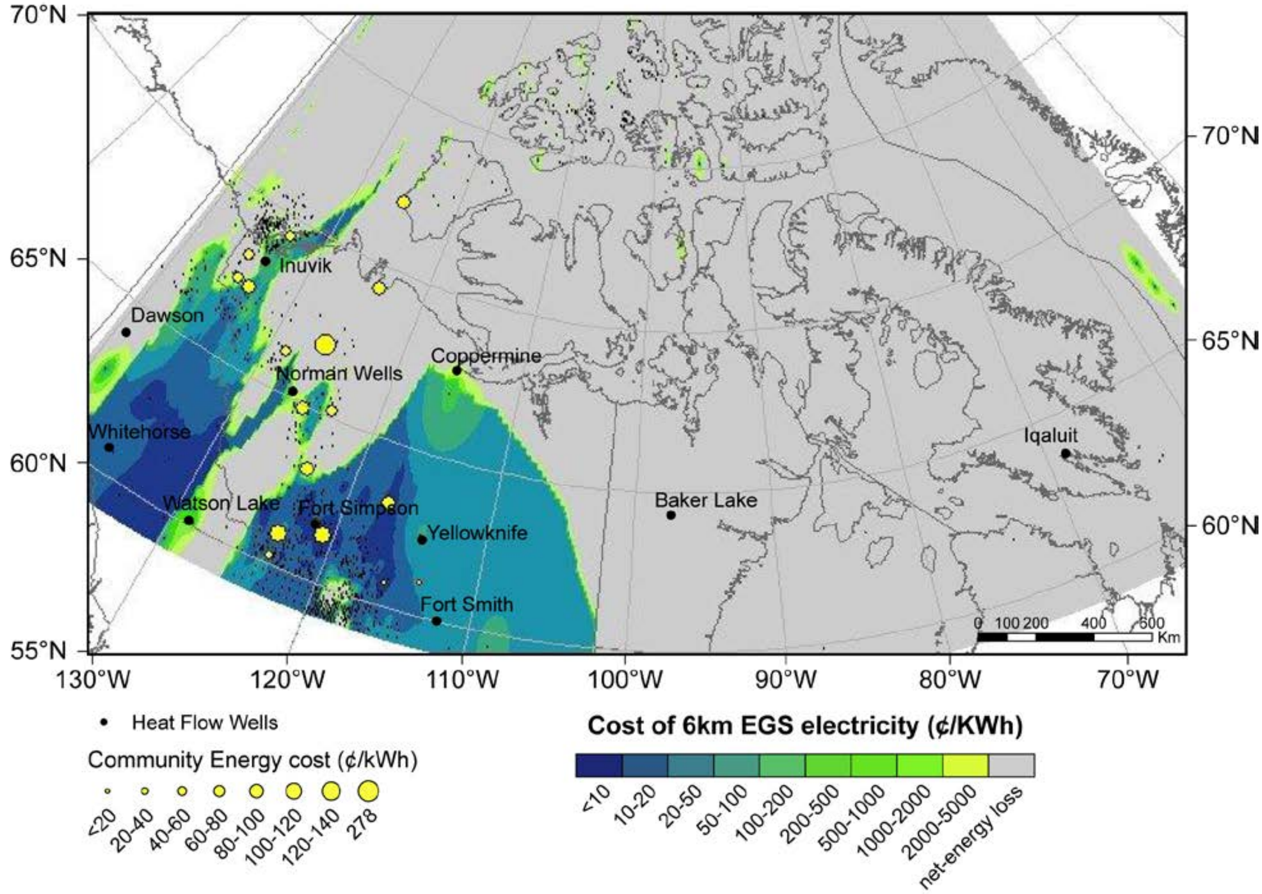

Figure 5.2: Cost of electrical energy for the modeled EGS system 6km deep. Contours are in c/kWh.

5.2 Thermal Energy

We also examined available thermal energy in northern Canada (Fig. 5.3) to examine potential economic use of shallower geothermal resources. In this case we model a potential 2 km deep resource that is able to support an assumed 30 kg/s flow rate. We assumed a 30 ^{o}C temperature drop after waters are passed through heat exchangers with an assumed 0.9 efficiency for the heat exchangers. The cost of drilling and enhancing fractures for achieving better flow are major overnight investments for such a project to be relaxed over 15 years of the system operation. Other significant costs not considered in our previous calculations (Majorowicz and Grasby (2010b) are the cost of pumping and reinjection. This, at 2 pumps at 0.45 MW electrical, is even larger when the high cost of electricity in northern Canada is considered (50 cents/kWh assumed). The cost would be up to 25 m$ over 15 years and potentially higher.

Drilling 2 wells then that specifically target thermal energy at 2 km depth, could provide costs less than 10 c/kWh for thermal energy production greater than 20000 kWh yearly (Fig. 5.4) in some places in the southwestern part of northern Canada.

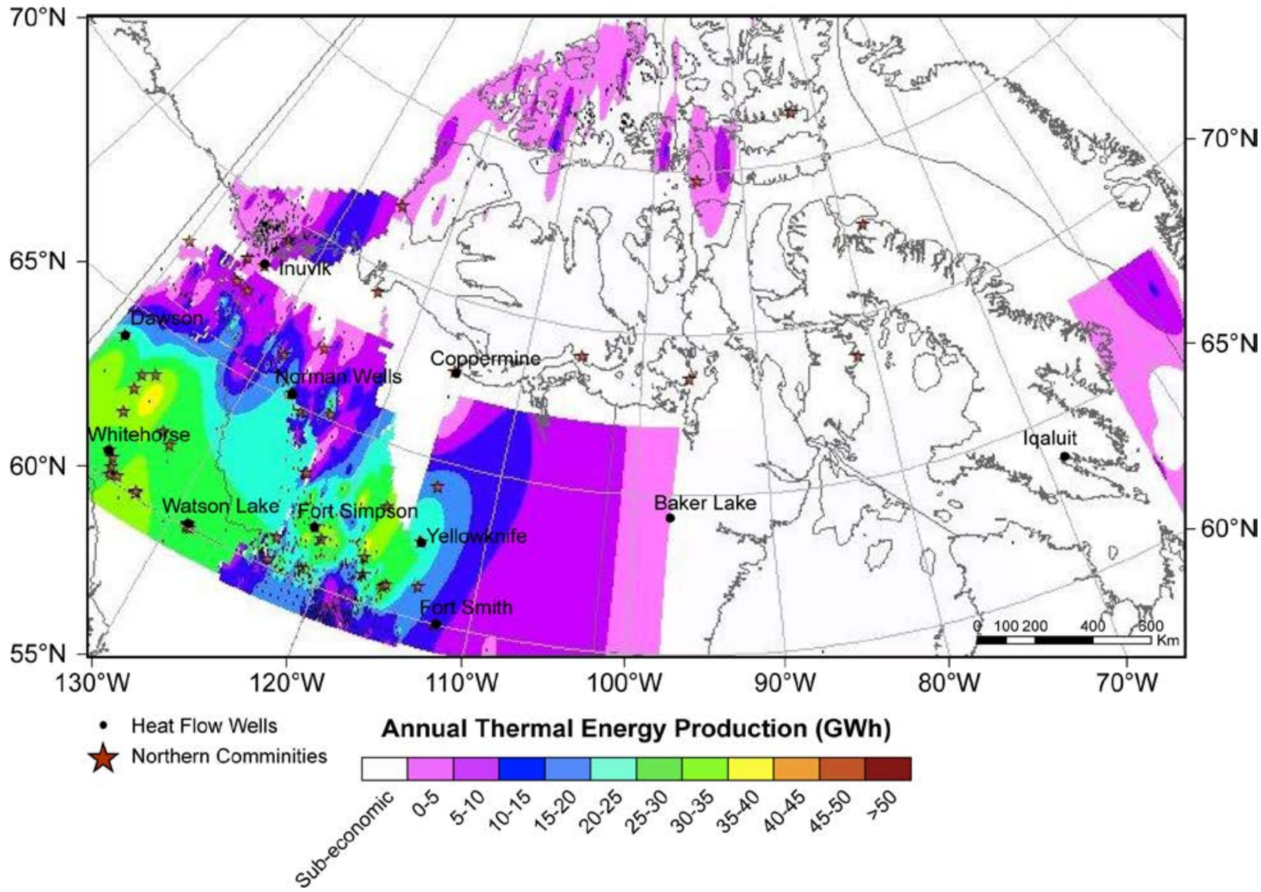

Figure 5.3. Patterns of potential annual thermal energy production for a 2 km deep geothermal resource.

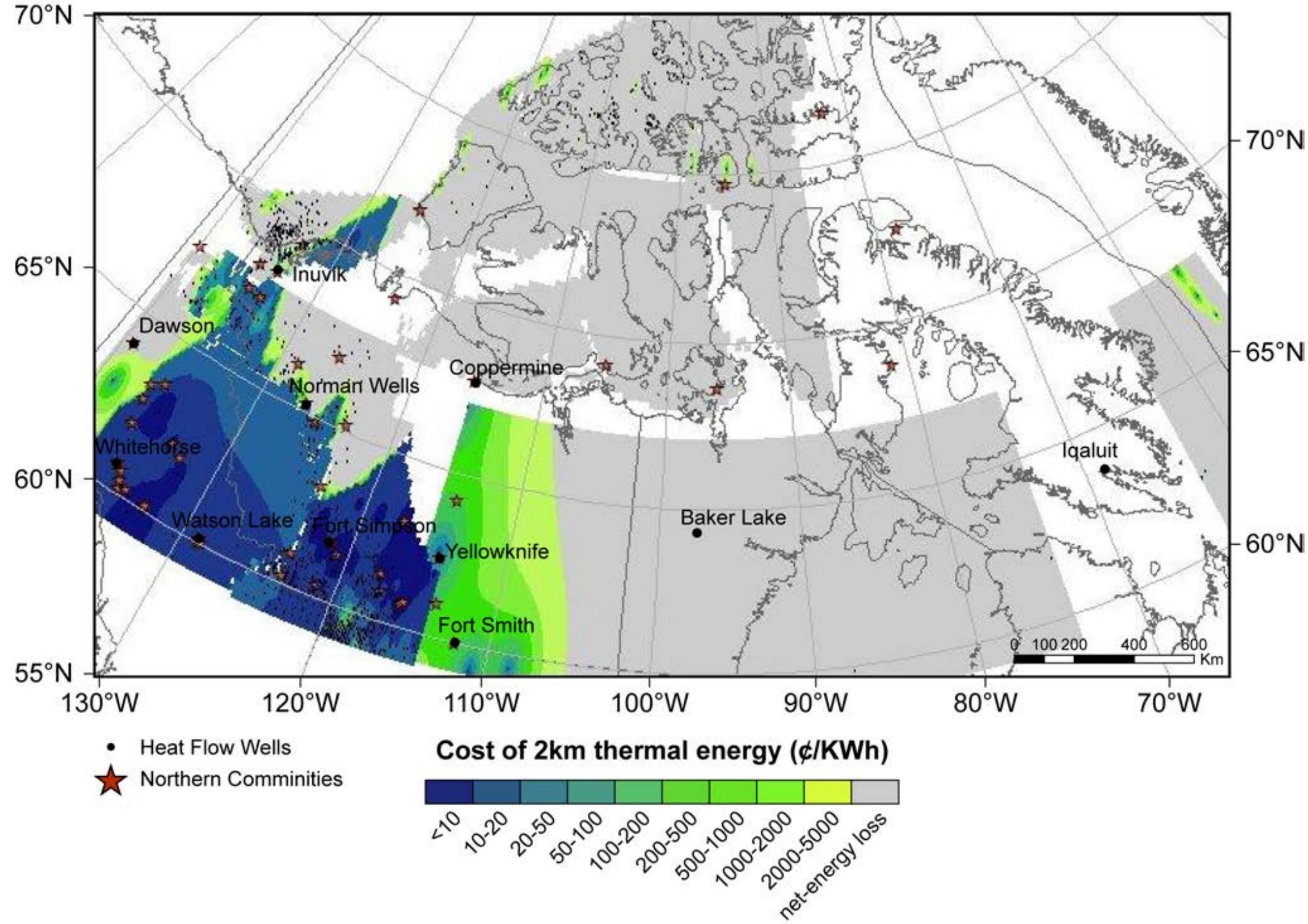

Figure 5.4. Patterns of cost of thermal energy for a 2 km deep geothermal resource. Contours are in c/kWh.

6. SUMMARY

The study results show that an EGS systems using two production wells, sustaining a flow rate of 30 kg/s in the areas where temperature gradient is high (>30 mK/m) could be competitive compared to simply burning natural gas or diesel for the communities in northern Canada. Higher gas prices and carbon taxes will all make the EGS more competitive. Generating electrical energy is a viable option for some of the northern communities mainly in the west-southwestern parts north of 60°. This can be achieved by deep EGS systems producing both electrical and thermal energy. Prelimenary estimates show that for these areas costs are comparabile to, or lower than, current electricity generating turbines and heating run on diesel or other high emission fuels.

In contrast, there are also large areas of northern Canada where geothermal development would be clearly not economical as the amount of energy needed to put into the system (pumping etc.) is larger than energy available from the system. In addition, low geothermal gradients of the Canadian Shield make geothermal energy unsuitable for communities in that geologic setting.

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