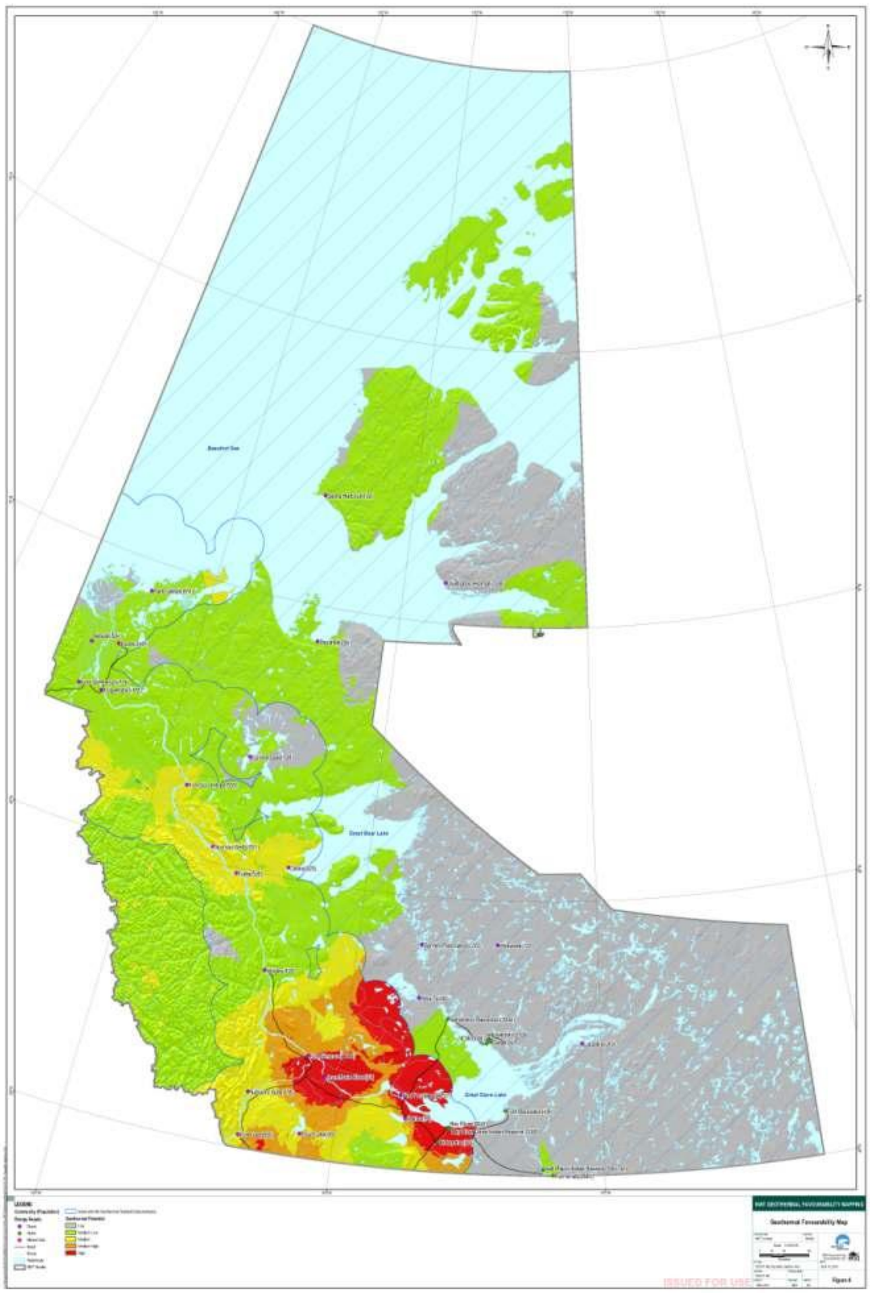
Geothermal Favourability Map

Northwest Territories



Northwest Territories Environment and Natural Resources

April 2010

EXECUTIVE SUMMARY

EBA Engineering Consultants Ltd. has prepared this report and a geothermal favourability map for the Government of Northwest Territories (NWT) to advance the understanding of the potential for geothermal energy production in the NWT. The results follow a comprehensive search of existing data provided by a number of sources including the NTGO (Northwest Territories Geoscience Office), NRCan, CanGEA, Geological Survey of Canada (GSC), and Government of Yukon Department of Energy Mines and Resources.

The most relevant existing information regarding geothermal potential is temperature data from oil and gas exploration boreholes in the Western Canadian Sedimentary Basin, the Mackenzie Corridor and Mackenzie Delta. Geothermal gradient derived from subsurface temperature data provides direct evidence of geothermal favourability (cf. Figure 6). Other regions, such as large portions of the Cordillera, the Canadian Shield and the Arctic Platform lack this direct geothermal gradient data and in theses areas geology, seismicity, and proximity to known thermal springs were used to evaluate geothermal favourability.

The favourability map integrates infrastructure data for the NWT, including roads, community power sources (diesel, hydro, and natural gas), community populations, and electrical grids obtained from a variety of sources including NTGO, Statistics Canada, Northwest Territories Power Company (NTPC), and the GNWT Electricity Review.

For geothermal favourability ranking in areas with geothermal gradient data, bottom hole (BHT) and drill stem test (DST) temperatures were limited to depths greater than 1550 ft (about 475 m). Geothermal gradient data was ranked to limit the influence of outliers and the radius of influence of each well was 50 km. Distinct anomalies occur in the southern Mackenzie Basin (> 60°C/km), and in the Mackenzie Corridor in the areas of Tulita, Deline, Norman Wells, Fort Good Hope and south of Fort McPherson (40-55°C/km). Table E-1 outlines the geothermal favourability ratings.

TABLE E-1: GEOTHERMAL FAVOURABILITY RATINGS

RATING	Geothermal Gradient(˚C/km)	FAVOURABILITY
LOW	< 30	below global average; low likelihood of development
LOW-MEDIUM	> 31-40	temperatures at about 2 km to 2.5 km depth may be high enough to operate an Organic Rankine Cycle power plant
MEDIUM	> 40-50	temperatures at about 2 km depth would likely be high enough to operate an Organic Rankine Cycle power plant
MEDIUM-HIGH	> 50-55	temperatures at about 2 km depth are likely high enough for efficient operation of an Organic Rankine Cycle power plant at temperatures over 100°C
HIGH	> 55	temperatures at a depth of 2 km to 3 km may be high enough to produce steam for a conventional geothermal power plant

Geothermal favourability ranking in areas without geothermal gradient data considered geology region, proximity to hot springs and seismicity in 1 km^2 cells. The six geological regions of the NWT were ranked from 1 to 5. The Cordilleran Orogen was ranked 5. The WCSB and the Mackenzie Delta/Beaufort Area, Arctic Continental Shelf, Innuition Orogen and Arctic Platform were ranked 3. The Canadian Shield was ranked 1. Section 4 of the report provides a discussion of the geothermal potential of the geology regions.

Hot springs in the NWT have surface water temperatures ranging from 8°C to 64°C. The favourability score within each 1 km^2 area was influenced by proximity to and temperature of each hot spring within a 100 km radius. The results of geothermometer methods to estimate maximum subsurface temperatures using the chemical and/or isotopic composition of water samples from hot or warm springs were reviewed (Table 3). Most geothermometer temperatures are in the range of about 80-150°C, with some considerably higher temperatures estimated by the alkali-based geothermometers.

Seismicity is an indication of tectonic activity and active faults that are potential conduits of geothermal fluids (Blewitt et. al., 2002). Estimation of geothermal favourability considered the magnitude and distance from the cell of seismic activity.

Geophysical data can augment geothermal exploration. Regional data is mostly managed by the Geological Survey of Canada and includes Seismic, Aeromagnetic, Gravity, Digital Magnetic Data (Figure 4), Regional Magnetic Surveys, Detail Magnetic Surveys, Electrical Resistivity and Conductivity.

The favourability map (Figure 6) illustrates the results of the NWT geothermal assessment and segregates those areas with and without geothermal gradient data. Several areas of medium to high geothermal potential occur in the Mackenzie River basin extending from the Alberta and British Columbia border in the south to the Mackenzie Delta in the north. The Canadian Shield and the Arctic Islands have a low or low-medium geothermal potential. The Cordillera has medium-low to medium geothermal potential. Considerable uncertainty of the geothermal favourability mapping is inherent in those areas without geothermal-related data. The compiled data that were in a suitable format were used to build an ArcGIS database used to create the geothermal favourability map.

The Liard River and Southern Mackenzie River Basin includes the highest geothermal gradients measured in the NWT and has been identified as the largest known deep geothermal anomaly in Canada (Grasby et al., 2009). The geothermal gradient near Fort Simpson and Fort Providence is estimated to be in the range of about 50 to 60°C/km, which, extrapolated to a depth of 2 to 3 km, is 100°C to 180°C, sufficient for efficient operation of a binary cycle geothermal power plant. Geothermal development may prove to be a power generation option for these communities and also Hay River. The thermal anomaly in this region suggests that sufficient energy is available at reasonable depth and within range of the community to derive both heat and electricity from the subsurface with a payback period as short as 5 years (Ghomshei, 2009). The source of the elevated geothermal gradient is unproven, but it may be due to increased heat generation from radioactive particles in the basement rock (Lewis et al., 2003) and/or enhanced mantle heat flow (Majorowicz, 1996).

The Mackenzie Corridor, which includes the communities of Deline, Tulita, Norman Wells, and Fort Good Hope, has a medium geothermal favourability, with geothermal gradient values of about 45°C/km and potential subsurface temperatures at 2 to 3 km depth of 90 to 135°C, sufficient for both district heating and geothermal power generation.

Data gaps precluded definitive assessment of geothermal favourability in areas of the NWT that did not have geothermal gradient data compiled from deep well drilling. Further regional geophysics programs, including seismic, would be useful.

In those areas identified as having favourable geothermal development potential, further geothermal exploration should be focused on areas located close to communities. In these areas, further geological exploration could include review of existing information, detailed geological mapping and structural analysis and geophysics to identify appropriate sites for exploration drilling.

The typical progression of geothermal development includes a reconnaissance study, pre-feasibility study, feasibility and resource confirmation, geothermal resource development and power plant installation and commissioning. Costs for pre-feasibility studies leading to deep drilling for pre-development could be in the order of $500,000. Drilling of deep holes for final assessment of the resource that could be included in the developed geothermal field would be a multi-million dollar undertaking.

Geological, hydrogeological, and geophysical data collected from a detailed exploration program would be used to develop a geothermal model of the depth and extent of a geothermal reservoir for the eventual design of a geothermal field with production and injection wells.

TABLE OF CONTENTS

PAGE

EXECUTIVE SUMMARY i
1.0 INTRODUCTION 1
2.0 SCOPE OF SERVICES 1
3.0 OVERVIEW OF GEOTHERMAL DEVELOPMENT TYPES 1
4.0 METHODS 3
4.1 Existing Data 3
4.1.1 Geological Data 3
4.1.2 Data on Known Hot Springs 4
4.1.3 Borehole Data 4
4.1.4 Infrastructure Data 4
4.1.5 Geophysical Data 4
4.2 Favourability Mapping 7
4.2.1 Geothermal Favourability Ranking in Areas with Geothermal Gradient Data 8
4.2.2 Geothermal Favourability Ranking in Areas without Geothermal Gradient Data 9
5.0 RESULTS 11
5.1 Geological Information 11
5.1.1 Arctic Continental Shelf 12
5.1.2 Innuitian Orogen 12
5.1.3 Arctic Platform 13
5.1.4 Cordilleran Orogen 13
5.1.5 Western Canadian Sedimentary Basin (Interior Platform) 14
5.1.6 Canadian Shield 16
5.2 Borehole Temperature DAta 16
5.3 Geophysical Data 17
5.4 Known Hot and Warm Springs 20
5.5 GIS Database 21
5.6 Geothermal Favourability Map 23
5.7 Geothermal Potential of Selected Areas in the NWT 24
5.7.1 Liard River and Southern Mackenzie River Basin 24
5.7.2 Mackenzie Corridor 25
6.0 DATA GAP ANALYSIS AND RECOMMENDATIONS FOR FURTHER EXPLORATION 26

TABLE OF CONTENTS

PAGE

6.1 Phased Approach to Geothermal Exploration and Resource Development ... 26
6.2 Geological Data Gaps and Geological Approaches to Geothermal Characterization ... 27
6.3 Geophysical Data Gaps and Geophysical Approaches to Geothermal Characterization ... 27
6.4 Potential Target Areas for Further Geothermal Exploration ... 28
6.5 Recommendations for Further Geothermal Exploration ... 29
7.0 CONCLUSIONS ... 30
8.0 LIMITATIONS OF REPORT ... 31
9.0 CLOSURE ... 32
TABLES ... 37
FIGURES ... 38
APPENDIX A ... 39

TABLES

Table 1: Existing Geothermal-related Information for the NWT
Table 2: Digital Aerial Geophysical Data Availability from Natural Resources Canada
Table 3: Hot and Warm Springs in the NWT
Table 4: Common Geothermometer Formulas
Table 5: Generic Cost Estimate for Geothermal Pre-feasibility Study

FIGURES

Figure 1: Geology Map of the NWT
Figure 2: Geothermal Gradient in the Interior Platform
Figure 3: Heat Flow in the Interior Platform
Figure 4: Gravity and Magnetic Data Coverage of Canada
Figure 5: GIS Data Compilation
Figure 6: Geothermal Favourability Map

TABLE OF CONTENTS

APPENDICES

Appendix A EBA's General Conditions

1.0 INTRODUCTION

EBA Engineering Consultants Ltd. (EBA) was retained by the Government of the Northwest Territories (GNWT), Department of Environment and Natural Resources to assess the geothermal potential and to produce a geothermal favourability map of the Northwest Territories (NWT). GNWT has identified geothermal energy as a potential option for the production of alternative energy. This project is intended to present a compilation of existing information and data with respect to the geothermal potential in the NWT and the interpretation of these data to assess the favourability of geothermal development.

2.0 SCOPE OF SERVICES

The scope of services for this project included:

- Compilation of existing information related to the geothermal energy potential in the NWT;
- Analysis of these data with respect to the feasibility of geothermal resource development in the NWT;
- Presentation of the results of this project as a NWT geothermal favourability map, which identifies areas of geothermal potential in gradients of low, medium-low, medium, medium-high, and high;
- Recommendations for further exploration and assessment of the geothermal potential in prospective areas; and,
- Preparation of this report summarizing the results of the data analysis with respect to the geothermal energy potential in the NWT.

3.0 OVERVIEW OF GEOTHERMAL DEVELOPMENT TYPES

Geothermal power is power extracted from heat stored in the earth. This geothermal energy originates from the original formation of the planet, from radioactive decay of radioisotopes like uranium, thorium and potassium, and from solar energy absorbed at the surface.

Geothermal energy can be used for electricity production, for commercial, industrial, and residential direct heating purposes, and for efficient home heating and cooling through geothermal heat pumps. The latter applications of using heat stored in the shallow subsurface in combination with heat pumps to heat buildings are usually referred to as geoexchange and are not further considered in this study. This project focuses on the use of deep geothermal resources for the generation of power and/or direct use of the thermal water for heating without the need of heat pump technology.

Two different geothermal resource types can be distinguished (e.g., Blodgett and Slack, 2009):

- A **conventional geothermal system** requires heat, permeability, and water. The heat from the Earth's core continuously flows outward. Sometimes the heat, as magma, reaches the surface as lava, but it usually remains below the Earth's crust, heating nearby rock and water – sometimes to levels as hot as several hundred degrees Celcius. When water is heated by the earth's heat, hot water or steam can be trapped in permeable and porous rocks under a layer of impermeable rock and a geothermal reservoir can form. This hot geothermal water can manifest itself on the surface as hot springs or geysers, but most of it stays deep underground, trapped in cracks and porous rock. This natural collection of hot water is called a geothermal reservoir.
- Although the deeper crust and interior of the Earth is universally hot, an **enhanced geothermal system** lacks two of the three ingredients required for a naturally occurring geothermal reservoir: water and interconnected open volume for water movement. Producing electricity from this naturally occurring hot, but relatively dry rock requires enhancing the potential reservoir by fracturing, pumping water into and out of the hot rock, and directing the hot water to a geothermal power plant. Research applications of this technology are being pursued in the U.S., France, Australia, and elsewhere. Enhanced geothermal systems are also sometimes – especially in Europe – referred to as hot dry rock systems.

There are four commercial types of geothermal power plants: flash power plants, dry steam power plants, binary power plants, and flash/binary combined power plants:

- **Flash Power Plant**: Geothermally heated water under pressure is separated in a surface vessel (called a steam separator) into steam and hot water. The steam is delivered to the turbine, and the turbine powers a generator. The liquid is injected back into the reservoir.
- **Dry Steam Power Plant**: Steam is produced directly from the geothermal reservoir to run the turbines that power the generator, and no separation is necessary because wells only produce steam. The image below is a more simplified version of the process.
- **Binary Power Plant**: Recent advances in geothermal technology have made possible the economic production of electricity from geothermal resources much lower than 150°C. Known as binary geothermal plants, the facilities that make this possible reduce geothermal energy's already low emission rate to zero. Binary plants typically use an Organic Rankine Cycle system. The geothermal water heats another liquid which boils at a lower temperature than water. The two liquids are kept completely separate through the use of a heat exchanger, which transfers the heat energy from the geothermal water to the working fluid. The secondary fluid expands into gaseous vapour. The force of the expanding vapor, like steam, turns the turbines that power the generators. All of the produced geothermal water is injected back into the reservoir.

- **Flash/Binary Combined Cycle**: This type of plant, which uses a combination of flash and binary technology, has been used effectively to take advantage of the benefits of both technologies. In this type of plant, the portion of the geothermal water which 'flashes' to steam under reduced pressure is first converted to electricity with a backpressure steam turbine and the low-pressure steam exiting the backpressure turbine is condensed in a binary system.

4.0 METHODS

4.1 EXISTING DATA

EBA conducted a comprehensive search for existing data for the assessment of geothermal potential in the NWT. Some existing information was provided by the Department of Environment and Natural Resources, GNWT. The main sources of information were geological and scientific databases available through the internet. Search terms for this data included: geothermal, hot springs, heat flow, heat generation, temperature, geothermal gradient, and borehole temperature. Internet databases searched included:

- GEOSCAN, bibliographic database for scientific publications of the Earth Sciences Sector (ESS) of Natural Resources Canada (NRCan);
- Online Gateway of the Northwest Territories Geoscience Office (NTGO);
- CanGEA website;
- Google Scholar; and,
- GeoScienceWorld

In addition to internet searches, EBA also contacted relevant government agencies to obtain additional information that is not readily available online. Government agencies contacted include:

- Geological Survey of Canada (GSC);
- NTGO;
- Library of the Department of Energy, Mines, and Resources (EMR), Government of Yukon

Table 1 provides a list of all resources compiled. Data formats include maps, reports, presentations, data compilations, cross sections, report figures and websites.

4.1.1 Geological Data

Geology information for the Northwest Territories has been compiled by the NTGO and multiple reports have been prepared by the GSC. The GIS polygons of geology in the NWT were obtained from the NTGO. Reports on the geology of the NWT were obtained from the EMR Yukon, NRCan, and NTGO Libraries.

4.1.2 Data on Known Hot Springs

Hot springs are an important indicator of geothermal activity. Hot spring locations in the NWT were compiled from several sources including Crandall and Sadlier-Brown (1976) and unpublished data by the Protected Areas Strategy of the NWT (PAS). These two sources appear to be the most comprehensive compilations of hot springs locations in the NWT and further searches did not result in any additional springs. Springs included in the PAS compilation were those described as hot or warm and springs above 10°C.

4.1.3 Borehole Data

Deep borehole temperature data is the most direct information on geothermal potential. Oil and natural gas exploration boreholes are often drilled to depths of several kilometres. Those boreholes provide invaluable information about the subsurface temperature regime. The Western Canadian Sedimentary Basin, the Mackenzie Corridor and the Mackenzie Delta have extensively been drilled due to their oil and gas potential and thus provide important data with respect to the assessment of the geothermal potential of these regions. However, only some of the existing data is publicly available. A significant portion of these data is proprietary and held by oil and gas companies. Majorowicz and Morrow (1998) published subsurface temperature and heat flow data from 595 boreholes in the Northwest Territories and Yukon. Further data was used by GSC (2009) but cannot be made available for this study due to confidentiality agreements between the GSC and industry partners.

4.1.4 Infrastructure Data

Infrastructure data for the NWT includes road maps, community power sources (diesel, hydro, and natural gas), community populations, and electrical grids. This data was obtained from a variety of sources including NTGO, Statistics Canada, Northwest Territories Power Company (NTPC), and the GNWT Electricity Review.

4.1.5 Geophysical Data

Geophysical data may play an important role for detecting and delineating geothermal resources in the Northwest Territories. The search of the existing geophysical data from the NWT comprised three tasks:

- Understanding the likely geophysical anomalies produced by geothermal resources;
- Applying criteria to the search for geophysical data to discount information that is either too deep or too shallow in origin, and subdividing the target information into reconnaissance and detail data; and,
- Identifying sources of information.

Disturbances to the geothermal gradient that constitute a potentially exploitable resource may be manifested in numerous physical changes that give rise to measurable geophysical anomalies. Some of these anomalies are directly characteristic of geothermal activity, but most are merely indicators that require correlation with chemical, geological and structural information. Manzella (2008) describes – in terms clear to the non-specialist – the nature and application of geophysical data used in the search for potential geothermal energy resources. Two parameters that limit the range of information likely to be useful in the search for potential geothermal energy sources are:

- The reservoir depth should lie between 1-4 km; and
- The associated intrusive event should have occurred less than one million years ago.

From these parameters it may be inferred that potential geothermal resources may be identified through continuing Earth response to the causal recent magmatic intrusions, and that a range of geophysical techniques presently used for hydrocarbon and mineral exploration might produce useful information as a by-product.

Suggested potentially useful geophysical information includes (e.g., Manzella, 2008; Keary et al., 2002; Spichak and Manzella, 2008; Thanassoulas, 1991; Ward, 1975):

- Level of seismicity – recent magmatic intrusions are likely associated with seismic activity. Zones of persistent seismic activity may, conversely, be associated with thermal phenomena.
- Electrical conductivity – minerals dissolved in heated groundwater may give rise to increased electrical conductivity measurements. Increased temperatures cause decreases in fluid and rock resistivities; a similar effect is observed in rocks due to hydrothermal alteration processes.
- Seismic velocity – fractured rock that offers pathways for increased groundwater circulation will be of lower seismic velocity and lower Poisson's ratio than competent rock of a similar type. Deep seismic data may identify suspected regions of plutonic emplacement by their anomalous velocity with respect to the country rock, or lack of internal reflectors.
- Density – gravity data may indicate areas of density anomalies. These may indicate negative anomalies caused by the presence of lower-density silica-rich plutonic intrusions, or zones where less competent rock likely to offer fluid circulation pathways. Alternatively, positive anomalies may be associated with hydrothermal alteration of rocks overlying the source, as reported from areas of California (Ward, 1975).
- Magnetic field strength – magnetic anomalies indicate changes in geology. This information can be used to infer the presence of veins, faults, ore bodies, or igneous rocks, all of which are indicators of structural changes possibly associated with a geothermal heat source.
- Electrical Potential – Circulating fluids are likely to give rise to differences in electrical potential. These can be measured on the ground using Self Potential techniques.

- Geophysical well logs provide detailed vertical profiles through the bedrock and may provide useful point data on geological structure.

The density and extent of geophysical data coverage afforded varies with survey technique and application. In most cases, geothermal prospecting will be a secondary use for the data, which will have been acquired on survey patterns appropriate to the primary aims of mineral and hydrocarbon prospecting.

- Seismicity data is acquired through passive (Kearey, Brooks and Hill, 2002), long-term monitoring and inversion of earth tremor travel times. Monitoring stations can be hundreds or thousands of kilometres apart, and data provide a general indication of event location. For more detailed studies, a dedicated survey is required. Data from the latter type of survey represent a tiny subset of the total volume of information available.
- Gravity and magnetic reconnaissance data are acquired through ground measurements or aerial surveys, flown in regular grids over wide expanses of land. The latter is ideal for basic geothermal zone identification, and represents a key data resource. However, airborne gravity may still be prohibitively expensive for many projects. These techniques are also passive, i.e. they use receiving equipment to measure natural potential fields. As such, data from successive surveys are reasonably easily integrated to form maps of increasingly wide and/or detailed coverage.
- Electrical conductivity data can be acquired aerially, using electromagnetic instruments, or on the ground by various means. The techniques require active survey methods, whereby the strength and configuration of the source determines the depth and resolution of the survey. As such, an area may be surveyed to provide conductivity data at scales inappropriate to geothermal prospecting, and coverage information cannot be taken at face value.
- Other techniques such as seismic reflection and refraction, self potential, and down-hole geophysical logging typically require terrestrial survey approaches. The data gathered is of limited use at the initial stages of resource identification, as its spatial extent is typically highly restricted. Therefore, of heavily-surveyed hydrocarbon-rich zones these categories of information are generally considered secondary, and are more likely to be acquired following initial reconnaissance-level identification of potential resources. With the exception of down-hole logging, these techniques are generally logistically, environmentally and financially less intensive than drilling, and cover greater areas for the level of investment required.

The discussion presented above has touched briefly on the type of information resources appropriate to this project. The actual inter-relationships of the various data types described and interpretation methods employed will not be discussed here. The remainder of this report considers the basic sources of information available.

The principal source of easily accessible geophysical information in Canada is the Canadian Federal Government, via the Geological Survey of Canada, part of Natural Resources

Canada (NRCan). Searches for independent sources generally lead back to this central repository of data, which includes information provided to the Government over many years by commercial and academic parties, plus data acquired on numerous federally, provincially, and territorially funded surveys.

Alternate likely information holders whose data is not presently held by the Federal Government include petroleum and mining stakeholders (e.g. diamond, uranium and precious metal mining companies), provincial or territorial Governments, and academic institutions. Exploration companies have made available large volumes of data and accompanying reports via the NTGO web site. Additional geophysical information has been acquired during pipeline construction projects, along narrow, lengthy linear corridors. In addition to the NRCan web site, the Northwest Territories Government web domain represents another important location for downloads of data and published papers.

Although much of the data contributed from private exploration firms (available through NTGO web site) is somewhat dated, there are also ongoing exploration programs that include government agencies as direct participants. Of note is the Secure Canadian Energy Supply program, which aims to discover more data concerning the Mackenzie Corridor and surrounding areas in the western Northwest Territories.

4.2 FAVOURABILITY MAPPING

Geothermal favourability depends on a number of factors that influence the geothermal potential of a region. GIS databases have proved to be useful to compile relevant geothermal information and to develop maps delineating areas of geothermal favourability (Noorollhi et al., 2007; Coolbaugh, et al., 2002). The geothermal-related information, such as regional geology, geological structures, subsurface temperature data, and surface geothermal features, is included into the GIS as evidence layers which are then used to infer the geothermal favourability at each point within the area of interest.

The evidence layers used to define geothermal favourability in this study are:

- Geothermal gradient;
- Regional Geology;
- Proximity to hot springs; and,
- Proximity to and magnitude of seismic events.

Based on data availability the geothermal favourability was determined separately for areas with geothermal gradient data and areas without geothermal gradient data (cf. Figure 6).

4.2.1 Geothermal Favourability Ranking in Areas with Geothermal Gradient Data

Evidence Layer 1 – Geothermal Gradient

Because subsurface temperature data give a direct indication of the geothermal potential at a well location, the geothermal favourability was solely determined based on the geothermal gradient in areas with geothermal gradient data.

Geothermal gradients are mostly taken from wells drilled and tested for hydrocarbon exploration compiled by the Geological Survey of Canada (Majorowicz and Morrow, 1998). The geothermal gradients were calculated from bottom hole temperatures (BHT) and drill stem test (DST) temperatures. BHT data were corrected by Majorowicz and Morrow (1998) for disturbance to temperature due to the drilling process. Only temperature data from depths greater than about 460 m (1,500 ft) were used for the analysis because it was noted that shallower BHTs were usually higher than the real rock temperature. The BHT and DST temperatures were used together with ground surface temperatures to calculate local geothermal gradients. For a more detailed discussion of the available borehole temperature data refer to Section 5.2.

As geothermal gradient data occur as single point samples, the radius of influence of each point was limited to 50 km. This was based on the calculation of the experimental variogram indicating a correlation length in the order of about 100 km. The radius of influence of 50 km therefore represents a conservative estimate. The geothermal gradient data were interpolated using the inverse distance weighting method.

In order to limit the influence of outliers in the geothermal gradient data, the data was separated into bins of temperature values with geothermal ratings from 0 to 5 assigned to each temperature range. Geothermal gradients below the global average background value of 30°C/km were assigned a rating of low. The following bins were used:

- < 30 = low
- > 31-40 = medium-low
- > 40-50 = medium
- > 50-55=medium-high
- > 55 = high

These bins were chosen based on the following rationale:

- A low geothermal favourability corresponds to a geothermal gradient that is below the global average of the geothermal gradient of about 30°C/km;
- A medium-low geothermal favourability indicates that the local geothermal gradient is slightly above the global average and subsurface temperatures at about 2 km to 2.5 km depth may just reach temperatures that are high enough to operate an Organic Rankine Cycle power plant;

- A medium geothermal favourability indicates subsurface temperatures at about 2 km depth that would likely be high enough to operate an Organic Rankine Cycle power plant;
- A medium-high geothermal favourability indicates subsurface temperatures at about 2 km that would be high enough to operate an Organic Rankine Cycle power plant with an increased efficiency at temperatures over 100°C; and,
- A high geothermal favourability indicates subsurface temperatures at a reasonable depth of 2 km to 3 km that may even be high enough to produce steam and operate a conventional geothermal power plant.

4.2.2 Geothermal Favourability Ranking in Areas without Geothermal Gradient Data

In areas without geothermal gradient data, the remaining three evidence layers were used to infer the geothermal favourability. The model domain, i.e., the portion of the NWT without geothermal gradient data, was discretized in a 1 km×1 km grid and a geothermal favourability score from 1 (low) to 5 (high) was calculated for each cell and for each evidence layer. The overall geothermal favourability score, i.e., the sum of the geothermal favourability scores for each evidence layer, determines the geothermal favourability of the cell and is shown on the geothermal favourability map.

The three evidence layers and associated geothermal favourability score calculation are described in more detail below:

Evidence Layer 1 – Geology (EL1)

The geological setting and history of an area is an important factor in determining the geothermal regime. Geologically young and tectonically active regions are known to be favourable for positive geothermal anomalies. Metamorphic and magmatic rocks hold the heat energy from their formation and can be sources for geothermal energy. Sedimentary basins can also be sources of geothermal energy in some cases. Geothermal energy in sedimentary basins originates from radioactive decay and heat conduction from deeper strata.

There are several geological provinces in the Northwest Territories. For the purposes of this report some of these have been combined based on geological characteristics. These provinces were each given a geothermal favourability score out of 5.

The **Cordilleran Orogen** is a young orogenic belt that is still tectonically active (as shown by seismic events in the Cordillera). As discussed in Section 5.1.4 this is the most probable area in the NWT for the occurrence of geothermal resources thus this region was given a geothermal favourability score of 5.

The **Western Canadian Sedimentary Basin,** which extends south to the USA border, is the Canadian portion of the North American Interior Platform. This area has several generations of sedimentation beginning in the Proterozoic with the opening of the Fort Simpson Basin. This area was assigned a geothermal favourability score of 3 based on the age of the rocks and their proximity to the recent Cordilleran Orogen as well as evidence of lithospheric thinning and high radioactive heat flow (Lewis et al., 2003).

For the purposes of this study the **Mackenzie Delta/Beaufort Area** is defined as the combined geological provinces of the Arctic Continental Shelf, Innuition Orogen and Arctic Platform as defined by the NTGO. As this area contains an extinct orogen and basin sedimentation ranging from the Proterozoic to the Quaternary, and does not have evidence of recent tectonic activity, it was assigned a geothermal favourability score of 3. The geothermal rating of these rocks was based on the age and nature of the rocks. There is no inherent heat in the sedimentary column; however, there is the potential for high heat flow from thin lithosphere and radioactive decay in basement materials (Lewis et al., 2003).

The region defined as **Archean Crust** contains the Slave, Bear and Churchill Provinces. This area is comprised of stable Archean cratonic rocks. The most recent tectonic activity in these rocks occurred during the Proterozoic with the collision of the Hottah terrane with the Slave Province. The most recent igneous activity includes Cambrian to Eocene aged kimberlites, but these are in limited numbers and very limited areas. Due to the expected low heat flow in the Archean aged rocks, this region was assigned a geothermal favourability score of 1.

Evidence Layer 2 – Hot Springs (EL2)

Hot springs are direct surface expressions of geothermal reservoirs. Springs included in this data compilation ranged in temperature from 8°C to 64°C. Hot spring data were compiled by Protected Areas Strategy of NWT (unpublished data), Grasby et al. (2009) and Crandall and Sadlier-Brown (1976).

The influence of each hot spring was limited to a radius of 100 km. The geothermal favourability score for each cell within a 100km distance to a hot spring out of a total possible score of 5 is calculated using the following equation:

Hot spring geothermal favourability score = ((1/distance from model cell to hot spring) * hot spring temperature).

To scale this to a value out of 5, the previous calculation is divided by 1/5th of the maximum calculated value to yield a maximum geothermal rating of 5.

By taking the inverse of distance to a hot spring this calculation gives the highest geothermal favourability score at the hot spring vent.

Evidence Layer 3 – Seismicity (EL3)

Seismicity is an indication of tectonic activity and of active faults that are potential conduits of geothermal fluids (Blewitt et. al., 2002). The seismic geothermal favourability score of a model cell is calculated using the following equation:

Seismic geothermal favourability score = (magnitude of event*(1/distance of model cell from epicentre))/0.2*maximum

This calculation yields a maximum seismic geothermal favourability of 5.

Overall geothermal favourability

The overall geothermal favourability score of a model cell was calculated from the geothermal favourability scores of each evidence layer:

Overall geothermal favourability score = EL1 + EL2 + EL3

This allows a possible maximum favourability score of 15. The favourability score was then rescaled to a maximum score of 5 corresponding to the following favourability ranking:

- Overall geothermal favourability score of 1 – low
- Overall geothermal favourability score of 2 – medium-low
- Overall geothermal favourability score of 3 – medium
- Overall geothermal favourability score of 4 – medium-high
- Overall geothermal favourability score of 5 – high

5.0 RESULTS

5.1 GEOLOGICAL INFORMATION

The Northwest Territories covers a vast northern landscape, spanning the top one-third of the northern latitudes from the 60th parallel to the North Pole. The location of the Northwest Territories is tectonically significant in that it straddles the contact of the ancient North American Plate with the younger accreted terranes at the west edge of North America. Within this expanse, six geological regions are recognized (Figure 1):

- Arctic Continental Shelf (arctic coast)
- Innuitian Orogen
- Arctic Platform
- Cordillera (west of and including the Rocky Mountain foothills)
- Interior Platform
- Canadian Shield

Notable on a continental scale is the contact of the relatively young (< 65 Ma [million years before present]) successive episodes of terrane accretion that form the modern outline of the western part of the continent with the westerly sloping Precambrian (> 545 Ma) crystalline basement of Ancestral North America that bisects the NWT. Also, a major geological structure, the Great Slave Lake Shear Zone, which includes the Hay River Fault and the McDonald Fault, crosses the southern region and separates the Slave Province from the Rae Craton of the Churchill Province. Major faults at the contact of the continental margin with the North American craton could form a potential conduit to deep sources of crustal heat.

5.1.1 Arctic Continental Shelf

The Arctic Continental Shelf is located along the northwest coast of the mainland and outer arctic islands in the Mackenzie Delta and Beaufort region and includes the Arctic Coastal Plain (an area of young sediments) and the Arctic Continental Slope (Arctic Islands and Oceanic Crust of the Arctic Ocean). The geology of the Arctic Continental Shelf (Beaufort Shelf) consists of young supracrustal sedimentary rocks (65 Ma to present). Supracrustal rocks were deposited on the existing basement rocks of the crust (Shield) and may be further metamorphosed from both sedimentary and volcanic rocks. The trend of faulting is generally north-northeast with a small area of east-west trending faulting at the outer southwest coast.

The stratigraphic sequence of the Beaufort Shelf is reported as Archean (3800 to 2500 Ma) crystalline basement overlain by Upper Cretaceous to Holocene (65 Ma to present) strata, which are separated from older strata by a significant tectono-stratigraphic boundary. (Dixon and Dietrich, 1990). In other areas, stratigraphy overlying the Shield rocks spans 1000 Ma from Cenozoic to Upper Proterzoic (Gabrielse and Brookfield, 1986). To date there has been little resource exploration in the Arctic Continental Shelf and there is little data on which to imply that this region could have an increased potential for geothermal development.

5.1.2 Innuitian Orogen

The Innuitian Orogen is a belt of mountains, uplands and lowlands located in the northern arctic islands, including Prince Patrick, Borden and Mackenzie King Islands and most of Melville Island. Its western extent into the Northwest Territories includes the Parry Islands Fold Belt on Melville Island and the Sverdrup Basin on Mackenzie King Island. The Innuitian Orogen is considered to be underlain by the northern margin of the North American craton (Canadian Shield) and is characterized by southwesterly or westerly depositional and structural trends.

The Innuitian Orogen comprises sinuous belts of folded supracrustal sedimentary rocks (65 to 650 Ma) and some older, metamorphic terrane. A strong, north and south-dipping fault trend is mapped in the central area with the fault orientation changing to north-south on the western margin. Four major stratigraphic successions are recognized: Canadian Shield, Franklin mobile belt rocks, Sverdrup and Wandel Sea basins, and Arctic Continental Terrace ranging from 1600 Ma to present. To date there has been little resource exploration in this region and there is little evidence to suggest an increased potential for geothermal development.

5.1.3 Arctic Platform

The Arctic Platform is a broad belt of plains and plateaus that extends west into the northern Northwest Territories and includes the Melville Basin, Minto Arch and part of the Wollaston Basin. It is underlain by successions of supracrustal sedimentary rocks (650 Ma to present) that have not been folded or faulted on a regional scale. Stratigraphy is dominantly Paleozoic (650 to 248 Ma) sedimentary rocks on a peneplain surface of Precambrian (>545 Ma), mainly crystalline basement of the Canadian Shield (Trettin, 1991).

The geological environment of the Arctic Continental Shelf, Innuitian Orogen and Arctic Platform is not considered optimal for geothermal development potential. Little geothermal-related information is available for this area. However, heat flow seems to be lower than average and combined with very low surface temperatures, the geothermal potential of this region is probably low (Jessop, 2008).

5.1.4 Cordilleran Orogen

The Cordillera is characterized as an imbricated succession of dominantly deformed and thrust sedimentary rocks formed by folding and faulting with an express eastward direction of tectonic transport toward the North American craton (Shield). It is the western accreted margin of North America and includes the Rocky Mountains and other ranges. Cordilleran geology includes sedimentary and intrusive supracrustal rocks that range in age from Mesozoic (65 Ma) to Neo- and Meso-Proterozoic (650 to 1600 Ma).

The mountain ranges of the western Northwest Territories are part of the Foreland Belt, which is the most easterly belt of the Cordillera. These include the Franklin and Mackenzie Mountains (Mackenzie Fold Belt), eastern margin of the Selwyn (Omineca) Fold Belt and a sliver of the Yukon Fold Complex on the northwest border. The Foreland Belt is composed of imbricated and folded miogeoclinal and clastic wedge assemblages deposited on and adjacent to the stable craton (Canadian Shield) of Ancestral North America (Gabrielse, 1991). In cross-section, the Foreland Belt contains an easterly tapering prism of mainly sedimentary rocks composed of several tectonic assemblages and Precambrian (> 545 Ma) crystalline basement gneiss adjacent to the Rocky Mountain Trench. Its eastern boundary is the eastern limit of deformation between deformed strata of the foothills and mountain systems on the west and flat-lying, undeformed strata underlying the Interior Plains to the east. The Selwyn Mountains are an uplifted region extensively underlain by metamorphic and granitic rocks.

Precambrian Basement can be identified beneath the Omineca and Foreland belts of the Cordillera as well as the Interior Platform. The overall age of basement beneath the Cordillera (except Proterozoic igneous events) ranges from 1840 to 2100 Ma with a few older Archean ages – no Archean rocks are known to occur beneath the Canadian Cordillera (except perhaps in the southernmost part) (Parish, 1991).

Heat flow in many parts of the Cordillera is above average indicating an increased geothermal potential in those areas (Blackwell and Richards, 2004; Jessop, 2008). The

Cordillera hosts many geothermal systems that are often associated with hot and warm springs at surface. Three different types of thermal springs have been described in the Cordillera: 1 – thermal springs associated with deep flow system in layered carbonate rocks; 2 – springs issuing from fractures in granitic or metamorphic rocks of non-volcanic regions; and 3 – springs located within or near belts of Quaternary volcanism.

Springs of the first type are often found in the Rocky Mountains, springs of the second type are usually associated with Tertiary plutons that are characterized by relatively high radiogenic heat generation. The third spring type is usually found in young volcanic belts (Jessop, 2008).

All known thermal springs in the NWT are located in the Cordillera. In the absence of young volcanic belts in the NWT, these springs can likely be classified as thermal springs of type 1 or 2.

5.1.5 Western Canadian Sedimentary Basin (Interior Platform)

The Western Canadian Sedimentary Basin (WCSB) spans the central north-south corridor of the Northwest Territories and includes the Peel Basin, Colville Fold Belt, Brock Inlier, Rocky Mountain Exogeosyncline, Fort Simpson Basin, Liard Basin and Tathlena Arch. It is a clastic wedge that ranges from 3 km to 5 km thick at its western edge (where it borders the Cordillera), thinning to zero at the Precambrian Shield margin (Price, 1994). The WCSB is the northern section of the continental Interior Platform (Interior Plains), a northwest-trending trough in front of the Cordillera that extends eastward to the Canadian Shield and south to the Canada – USA border.

Granitic Precambrian basement complexes of the Canadian Cordillera can be identified beneath the WCSB. Near Fort Simpson these Precambrian basement units have been aged by zircon composition at 1850 Ma (Parish, 1991). This age is similar to that of the Great Bear magmatic zone in Wopmay Orogen (1600 to 1900 Ma).

A major strike-slip fault underlying the WCSB extends northeast from Williston Lake in northwest British Columbia through Great Slave Lake (the Great Slave Lake Shear Zone - GSLSZ) into the Shield. The GSLSZ is reported to be at least 50 km wide with over 500 km of offset (Peirce, 1991). Vertical displacement and possibly horizontal offset are presumed to be present in Phanerozoic strata near the Hay River fault, which is coincident with the GSLSZ.

Liard Basin, a significant sub-basin of WCSB in the southwest corner of Northwest Territories, has been the target of significant oil and gas exploration. It is reported to include up to 5000 m of Paleozoic and Mesozoic sedimentary fill (Walsh, 2005). The western side is the Liard Fold and Thrust belt. The eastern boundary of the Liard Basin is delineated by the Bovie Fault System with parallel, north-south thrust faults interpreted at the sub-Cretaceous unconformity surface (MacLean and Morrow, 2004).

Fort Simpson Basin underlies WCSB sediments, formed on the west side of the Fort Simpson Terrane during extension (after about 1800 Ma) and received about a 20 km sequence of sedimentation (Cook, 1998). The Rocky Mountain Exogeosyncline is an extensive area east of the Mackenzie River and includes the west half of Great Bear Lake. It is characterized by ancient Precambrian rocks of the Shield covered by a progressively thickening wedge of late Palaeozoic sediments that remain nearly flat-lying or gently dipping.

The terrestrial heat in the WCSB may be from three sources: the mantle, the crystalline basement and the sedimentary rocks. On the basis of heat generation and transfer, the WCSB can be divided into a Lower and Upper Crust. The Lower crust of Archean and Proterozoic age apparently underlies most of Alberta (Theriault and Ross, 1990). The Upper Crust is typically a major source of terrestrial heat because of high concentrations of the three major sources of radioactive heat generation: U, Th and K.

Subsurface data is not available for all of this area with respect to its geothermal potential but parts of it have high heat flow (in excess of 90 mW/m2) and above average geothermal gradients. Jessop (2008) therefore concludes that the geothermal potential in this area might be significant, especially with applications for remote communities.

Majorowicz (1996) reports a large geothermal gradient anomaly in the Mackenzie Basin to the east of the Mackenzie Mountains. The data are based on temperature measurements - mostly in oil and gas exploration wells (data from 1146 wells in total) - deeper than 656 m (2000 ft). The average observed geothermal gradient in the Mackenzie Basin was (50 ± 14)°C/km compared to the mean geothermal gradient of the Prairie basin of (34 ± 6)°C/km. Geothermal gradients as high as 140°C/km were observed in the shallowest part of the Mackenzie Basin in southern NWT. Calculated heat flow values exceed 100 mW/m2 in most of the Mackenzie basin with an area of about 500 km by 300 km exceeding 80 mW/m2. This makes the so-called Northern Prairies Heat Flow Anomaly (NPHFA) the largest heat flow anomaly in Canada (Majorowicz, 1996). This heat flow anomaly is part of a string of high heat flow zones spreading from north to south in western Canada, mainly in the foreland of the Canadian Cordillera. The Mackenzie Mountains foreland north of the NPHFA includes a heat flow anomaly in the area of Norman Wells where a high heat flow value of 84 mW/m2 was observed. The origin of the high heat flow zones is widely unknown. Majorowicz (1996) speculates that the heat flow anomalies are caused by an elevated mantle heat flow at the western margin of the North American craton. However, Lewis et al. (2003) suggest that high crustal heat generation causes the high heat flow.

In summary, major fault zones such as those mapped in this region can indicate a favourable environment for elevated geothermal potential similar to geological models in other jurisdictions with high geothermal development potential. Data from oil and gas exploration boreholes has confirmed elevated geothermal gradient and high heat flow in parts of the WCSB.

5.1.6 Canadian Shield

The Canadian Shield is the ancient crust mostly Archean (> 2500 Ma) that forms the North American Plate, the largest Orogeny of the continent. The Shield makes up a large area of the Northwest Territories, covering the southeast quadrant east of the east shores of Great Bear and Great Slave Lakes. The Great Slave Lake Shear Zone bisects the Shield into the Rae Craton of the Churchill Province (southeast) and Slave and Bear Provinces (northwest).

Statistical analyses of composite samples from the exposed Canadian Shield indicate that the concentration of radioactive elements varies widely between the various tectonic provinces. The average heat-generation values are low for the Archean Superior and Slave provinces and high for the Proterozoic Churchill and Bear Provinces. The Great Bear Magmatic (Proterozoic) Arc – equivalent to the Bear Province – is a region of heat generation (Eade and Fahrig, 1971).

The basement rocks of the Canadian Shield forming the eastern part of the Northwest Territories are unlikely to yield geothermal resources. Although there is very limited geothermal-related data available for the Canadian Shield, Precambrian rocks can generally be characterized as low porosity and low permeability rocks. Fluid flow is widely restricted to fractures. Studies related to underground nuclear waste disposal have shown that water moves only in fractures and that drilling of a slim hole to assess the water movement and hydraulic properties of the formation creates significant changes to the water circulation system and prevents any effective understanding of the natural system. Furthermore, the terrestrial heat flow from the old crust beneath the shield is low, resulting in a generally low geothermal gradient. The combination of low porosity, low permeability, and low geothermal gradient means that the prospect for geothermal development is low (Jessop, 2008).

Deep, abandoned mines may have some potential for low-temperature geothermal development for heating purpose if the potential users are placed in close proximity to the mine workings.

5.2 BOREHOLE TEMPERATURE DATA

Majorowicz and Morrow (1998) compiled temperature data from 595 deep exploration wells in the Northwest Territories and Yukon. The authors considered only data from wells at depths greater than about 460 m (1500 ft). The bottom hole temperatures (BHT) or drill stem test temperatures (DST) and ground surface temperatures were used to calculate the geothermal gradient at each well location. The average error of the geothermal gradient estimate is $(10\pm5)\%$. The effective thermal conductivity was measured on rock samples of typical lithology types in the Western Canada Sedimentary Basin and estimated for the wells based on rock analysis and on average rock conductivities. The estimated range of error of the effective thermal conductivity is $16\pm6\%$. The geothermal gradient and effective thermal conductivity were then used to calculate the conductive heat flow for each well location.

Figures 2 and 3 show the spatial distribution of the geothermal gradient and heat flow in the areas where borehole data exist. The data were interpolated using the Kriging method implemented in the software Surfer. A variogram model was fitted to the data manually and used for the Kriging procedure. The inhomogeneous distribution of wells inevitably imposes limitations on the reliability of map patterns generated from these well data in regions with sparse data. In areas of good well coverage, the map patterns illustrated in Figures 2 and 3 are considered reliable. The interpolated geothermal gradients in areas with sparse data coverage are considerably more uncertain and should be interpreted with caution.

Most of the borehole data are concentrated in the Mackenzie Basin and Delta. Less densely spaced well coverage exists in the area along the Mackenzie River between the southwestern NWT and the Mackenzie Delta. However, the available data are still deemed sufficient to assess the geothermal regime on a large scale.

The geothermal gradient map (Figure 2) shows a distinct anomaly in the southern Mackenzie Basin with values of more than 60°C/km, which is significantly higher than the average background geothermal gradient of 34°C/km in the Prairie Basin.

Another less pronounced anomaly of the geothermal gradient with values of 40-55°C/km is located in the Mackenzie Corridor in the areas of Tulita, Deline, Norman Wells, Fort Good Hope and south of Fort McPherson. The wells in the Mackenzie Delta mainly show geothermal gradients of less than about 35°C/km.

The heat flow map (Figure 3) shows similar anomalies as the geothermal gradient with the most distinct anomaly in the southern part of the Mackenzie Basin and a weaker anomaly in the Mackenzie Corridor in the areas of Tulita, Deline, Norman Wells, Fort Good Hope and south of Fort McPherson.

5.3 GEOPHYSICAL DATA

Seismicity Data

The Geological Survey of Canada provides information from seismic monitoring stations online. The Northwest Territories contains a limited spread of monitoring stations (Inuvik and Yellowknife), which limits the value of the available seismicity information, both in terms of positional accuracy of foci, and the minimum size of events recordable. There is also some debate (e.g. Ward, 1975) as to the reliability of seismicity as an indicator for the presence of shallow plutons.

Published papers such as Ward (1975) and Manzella (2008) describe use of seismicity data, utilizing microseisms to gain details of local changes in seismic velocity, and hence potentially indicating thermal changes in the shallow crust. This type of investigation relies on field programs that deploy numerous seismographs for sufficient periods that allow recording of several tens of microseisms (often several weeks or more). This kind of data will only have been acquired by parties specifically searching for localized sources of seismicity, and will not be of use to regional scale reconnaissance investigations.

Canadian Aeromagnetic Database

The Canadian Aeromagnetic Data Base contains more than 12 million line km of regional total field survey data and high resolution detailed surveys. The aeromagnetic data has been levelled to a common datum, and levelled profiles and gridded data are now available for all ten provinces and the Yukon and Northwest Territories.

The database is available at:

http://gdrdap.agg.nrcan.gc.ca/geodap/home/Default.aspx?lang=e

Data can be downloaded directly and free of charge. There would be a lengthy period of downloading required to obtain all data available for the Northwest Territories, as files are supplied in individual surveys. Data is provided as Geosoft binary GRD files, which require an Oasis Montaj viewer (freely available from http://www.geosoft.com) to open and view.

There are also available numerous individual scanned paper maps of the magnetic field in the Northwest Territories. These are rather dated (mainly 1950s) but do offer an accessible representation of the data in PDF, MrSID and jp2 format.

Canadian Gravity Database

The entire data set is available as a 2 km grid which is updated annually to reflect recent data acquisition, as indicated on Figure 4. Data types available include:

- Bouguer anomaly on land, free air anomaly offshore
- Observed gravity
- Free air anomaly
- Bouguer anomaly
- Isostatic anomaly
- Horizontal gradient of Bouguer anomaly
- Vertical gradient of Bouguer anomaly

There are 670,000 available measurement points across Canada; these have been interpolated to form a 2 km grid. This grid is available free online. Individual points can also be purchased at $0.01/point, or $200 for the entire Canadian dataset (around 670,000 points).

Digital Magnetic Data

Magnetic data coverage is indicated on Figure 4, which shows separately representations of all coverage and data that has been levelled to a singular datum.

Regional Magnetic Surveys

These data encompass reconnaissance surveys that have been flown from the 1970s to present. Line spacing ranges from 800m to 2, 4, and 6 km, and the surveys were flown at a constant barometric altitude or in some instances, mean terrain clearance. Recorded parameters typically include: total field magnetics, radar and barometric altimetry, navigation information.

Detail Magnetic Surveys

These are target specific surveys with 300 m being the typical line spacing and 150 m mean terrain clearance (MTC) the flying height. Recorded parameters include some or all of the following: total field magnetics, radar and barometric altimetry, navigation information, vertical gradient magnetics, VLF-EM, several EM channels.

Electrical Resistivity and Conductivity Data

Thanassoulas (1991) details the methods by which electrical data may be used to detect and delineate geothermal resources. For reconnaissance surveys the typical means of acquiring electrical information is through airborne electromagnetic survey methods, including MagnetoTelluric (MT), Time Domain Electromagnetic (TDEM), Frequency Domain Electromagnetic (FDEM) techniques. On the ground, and therefore requiring greater acquisition time, these techniques are supplemented by DC resistivity (e.g. Electrical Resistivity Tomography and Induced Polarization), and Self Potential techniques.

Federal Government resources for electrical information in the Northwest Territories are detailed in Table 2.

Given the size of the Northwest Territories (1,140,835 km2), reports on the geophysical characteristics of individual areas are of limited use in geothermal reconnaissance, but may play a secondary role following identification of potential resources, if the area has previously been investigated for some other purpose.

Repositories for reports and papers include:

- NRCan (GSC) website;
- NTGO website; and
- Numerous scientific journals.

Publications and Open Files tend not to be presented in fixed geographic sets, and often several searches for likely place names, survey targets, projects and likely involved parties are required before the full literary resource is uncovered.

In addition to the sources described above, two projects likely to produce further documentation and potentially useful data are:

- Mackenzie Corridor Project: a major resource of seismic data and interpretation is being constructed under this project, in the Mackenzie Corridor area. The major stakeholders include oil, gas and pipeline companies, and several government departments. The project will involve reinterpretation of old seismic data and production of a multi-thematic digital geoscience atlas.

- In the north of NT the Slave Geological Province NATMAP project aims to better understand the geological resources. Several open files are available describing work undertaken on this project, as pay-per-download material.

Additional Territorial Government Resources

The NTGO website (http://www.nwtgeoscience.ca/services/index.html) makes available a vast resource of survey documentation provided by exploration companies, including descriptions of gravity, magnetic, electromagnetic, and radiometric surveys of specific claim areas. These reports are available as scanned paper documents, which may be of some use when interpreting data available from the NRCan. These reports are too numerous and widespread for a simple summary to be effective. While they are likely too site-specific to be of assistance during initial wide-scale reconnaissance for thermal resources, they may be of benefit for follow-up analysis of specific areas.

5.4 KNOWN HOT AND WARM SPRINGS

Information on known hot and warm springs in the NWT were compiled from Crandall and Sadlier-Brown (1976) and unpublished data by the Protected Areas Strategy of the NWT (PAS) (Table 3). Information on springs described in Crandall and Sadlier-Brown (1976) also include water chemistry results that were used to calculate geothermometer temperatures (Tables 3 and 4).

Geothermometer methods are used to estimate maximum subsurface temperatures using the chemical and/or isotopic composition of thermal water samples, e.g., collected from hot or warm springs. The methods rely on the assumptions that the dissolved and solid species coexisted and have equilibrated within the geothermal reservoir, that temperature is the main control on their ratio or concentration, and that re-equilibration has not occurred during ascent and discharge.

There are a wide range of empirical chemical geothermometer formulas in the literature. One group is based on the equilibrium reached among alkali elements (sodium (Na), potassium (K) and calcium (Ca); Fournier and Truesdell 1973). Another group is based on the solubility of various mineralogical forms of silica (SiO_2) in hot geothermal waters. Silica solubility is rate-dependent, so waters that gain silica at elevated temperatures only slowly release that silica as the waters cool (i.e., as they move upwards and discharge at the surface). For this reason, the silica content of discharging geothermal waters can be used to calculate the approximate maximum subsurface temperature at which the water acquired the silica content.

Some of the prominent formulas are presented in Table 4.

Because calcium is the dominant cation in all water samples collected, we have chosen to use the classic alkali formula no. 1 (Fournier and Truesdell 1973) with the constant term B = 1/3 (assuming subsurface temperatures are greater than 100°C) and the formula No. 3 (Diaz-Gonzalez and Santoyo, 2008) which has been updated using data from the world database of geothermal fluids.

For a silica geothermometer, we chose to use formula No. 9 (Verma and Santoyo 1995) since this is an update of Fournier's original formula and is applicable for temperatures ranging from 20 to 210°C. These formulae fit the hydrochemical setting and temperature ranges expected for the samples collected, and provide a reasonable estimate of subsurface temperatures for purposes of this reconnaissance study.

Most geothermometer temperatures are in the range of about 80-150°C with some considerably higher temperatures estimated by the alkali-based geothermometers. More detailed interpretation of the hydrochemistry of the thermal springs would be necessary to further assess the geothermometer results.

5.5 GIS DATABASE

A GIS database was prepared to compile all the geothermal information for the favourability map (Figure 5). The following is a list of layers included in the GIS database:

Base_IceBearingPF_NWTClip

- Contains records from "permafrost database 3.xls" included with Geological Survey of Canada Open File report No. 4173,
- Only records with base of ice bearing permafrost data available within the NWT are included

Communities

- Populated places of the NWT with population and energy supply information attached

Earthquake_NWTClip

- Data from the Seismic Hazard Earthquake Epicenter File included with Geological Survey of Canada Open File No. 6208
- This is a subset of the master file that includes only records within the NWT
- The MAG field indicates the magnitude of the earthquake and is the field used in the geothermal model

GeologicalProvs

- The NWT divided into its geological provinces
- Data is a modification of the Atlas of Canada Geological Provinces Dataset (Province names have been modified)

Known_Hot_Warm_Springs

- Name and type (hot or warm) of spring are available
- Dataset is for NWT only

- Temperature of 20°C assigned to all warm spring and 40°C assigned to all hot springs for modeling purposes

NWT_Faults

- Location and type of faults for the NWT
- Data provided by the NWT Geoscience Office

NWT_Geology

- Geology units for the NWT
- Data provided by the NWT Geoscience Office

Wells

- Well locations with geothermal gradient and heat flow attributes
- Some wells from the Yukon were in close enough proximity to use in the geothermal model for the NWT

Wells_NWTClip

- Same data as "Wells", but only records within the NWT are included
- Used for presentation purposes

GeoPot_WellAreas.img

- Geothermal potential results for the area of the NWT that has available geothermal gradient data (the area within a 100 km buffer of the wells layer)
- Values are meant to be classified into 5 categories:
- <30 = low
- >31-40 = medium-low
- >40-50 = medium
- >50-55=medium-high
- >55 = high

GeoPot_ NoWells.img

- Geothermal potential results for the area of the NWT that does not have geothermal gradient data available
- Results are based on a combination of geological province, hot spring, and earthquake layers
- Results are meant to be mapped as an equal interval classification with 5 categories (low, medium-low, medium, medium-high, and high)

5.6 GEOTHERMAL FAVOURABILITY MAP

The results of the geothermal favourability calculation as described in Section 4.2 are presented as a colour-coded geothermal favourability map in gradients of low, medium-low, medium, medium-high, and high (Figure 6). As described in Section 4.2, the NWT is separated into two areas with and without geothermal gradient data. The region of the Mackenzie River basin extending from the Alberta and British Columbia border in the south to the Mackenzie Delta in the north includes several areas of medium to high geothermal potential based on subsurface temperature data from oil and gas exploration boreholes. These areas will be further discussed in Section 5.7. The Canadian Shield and the Arctic Islands were identified as having a low or low-medium geothermal potential based on available geological and seismicity information. The Cordillera has medium-low to medium geothermal potential as determined based on the existing information on geology, seismicity, and known warm and hot springs.

Given the large territory-wide scale of this project and the limited geothermal-related data available, a considerable uncertainty is inherent with the geothermal favourability mapping. The geothermal favourability ranking in areas without subsurface temperature information is especially uncertain as it is entirely based on regional geology and seismicity information and the proximity to known thermal springs. Only a very rough estimate of the geothermal favourability associated with a considerable amount of uncertainty can be inferred based on this limited and indirect information. For example, the Cordillera with known geothermal activity may have a significantly higher geothermal potential in certain areas than determined during this study. More data and interpretation of these data on a more local scale is required to further assess the geothermal potential of specific areas within the Cordillera. However, most of the areas with a possible geothermal potential in the Cordillera are very remote and far away from any potential power consumer.

Geothermal gradient data provide direct information on the subsurface temperature regime in areas where this type of data is available. However, the geothermal gradient information used in this study is based on borehole temperatures that represent point-source information. For the purpose of inferring a geothermal favourability, this point-source information has to be spatially interpolated. The uncertainty in the geothermal favourability is therefore directly related to the spatial density of borehole temperature data within a specific area. Figure 2 shows the well locations where geothermal gradient data are available. The best data density and therefore the greatest confidence in the inferred geothermal favourability exist in the southern part of the Mackenzie River Basin and the Liard River Basin in the area of the communities of Fort Liard, Fort Simpson, and Fort Providence. Most of the remaining areas have only poor to fair data coverage which causes a significantly higher uncertainty with respect to the interpolation of the geothermal gradient and the geothermal favourability ranking. These areas also include the area to the east and north of Fort Providence that is indicated as having a high geothermal favourability. Although there are a number of oil and gas exploration wells located in this area that indicate high geothermal gradients, spatial data coverage is very limited and the uncertainty associated with the interpolation of the these data and the inferred geothermal favourability is significant and has to be considered when interpreting the results of this study.

5.7 GEOTHERMAL POTENTIAL OF SELECTED AREAS IN THE NWT

5.7.1 Liard River and Southern Mackenzie River Basin

A geothermal anomaly has been identified in the south western region of the Northwest Territories. Figure 6 is a map of this area showing the geothermal favourability of the area as determined by this study.

The area is located in a geothermal anomaly identified by downhole temperature measurements mainly in oil and gas exploration wells. This area includes the highest geothermal gradients measured in the NWT and has been identified as the largest known deep geothermal anomaly in Canada (Grasby et al., 2009).

The community of Fort Liard has already been pursuing geothermal development for power generation. Other larger communities that are located within the geothermal anomaly and may have the potential for geothermal development – both for district heating and power generation – include Fort Simpson, Fort Providence and Hay River. Hydropower presently meets the power generation requirements of Hay River and therefore geothermal development, at least for power generation, may not be of immediate interest. Fort Simpson and Fort Providence, however, are both currently using diesel power at very high costs and geothermal development might be a viable option for both power generation and district heating in these communities.

The geothermal gradient in the vicinity of Fort Simpson and Fort Providence is estimated to be in the range of about 50 to 60°C/km based on temperature data from hydrocarbon exploration drill holes. By extrapolating this estimated temperature gradient to a depth of 2 to 3 km, a temperature between 100°C to 180°C is expected. These temperatures would be sufficient for the operation of a binary cycle geothermal power plant. Binary cycle power plants can even be operated at water temperatures below 100°C. For example, Chena Hot Springs in interior Alaska have been operating a 400 kW Organic Rankine Cycle power plant with thermal water at a temperature of 74°C.

Fort Simpson and Fort Providence are located near the convergence zone (fossil subduction zone) of the collision between the Hottah terrane and Fort Simpson volcanic arc on the north-eastern edge of the Western Canadian Sedimentary Basin (WCSB). Geothermal studies in the WCSB have shown that the geothermal gradient is low in the south-eastern part of the basin and increases toward the north-eastern corner of the basin in the NWT. The reason for this increase in geothermal gradient is subject to debate and multiple theories have been presented. These include increased heat generation from radioactive particles in the basement rock (Lewis et al., 2003) and enhanced mantle heat flow (Majorowicz, 1996) in the northern region of the WCSB.

Geophysical surveys in this area have included magnetotelluric surveys, seismic reflection studies, gravitational surveys and magnetic surveys. Seismic reflection studies conducted across this region include the Lithoprobe Snorcle transect 1 which has been utilized to interpret overall structure across the WCSB in this region including a relict subduction zone between the Fort Simpson terrane and the Hottah terrane. The seismic interpretation has been compiled from multiple sources by Canada's National Lithoprobe Geoscience Project. Magnetotelluric sounding shows higher conductivity beneath the Fort Simpson basin than surrounding areas and is interpreted as a possible indication of a geothermal heat source (Ghomshei, 2009).

Previous studies in the Fort Simpson area have outlined the feasible options for geothermal energy production in this community (Ghomshei, 2009). Due to the high heat flow, options include geothermal exchange for heating purposes, geothermal exploitation for energy production or the cogeneration of heat and energy from the resource. The thermal anomaly in this region suggests that sufficient energy is available at reasonable depth and within range of the community to derive both heating and electricity from the subsurface. The cost of electricity in Fort Simpson is currently as high as $0.60 per kWh, and the payback period on a geothermal plant is expected to be as short as 5 years (Ghomshei, 2009).

It should be noted that the geothermal favourability ranking is solely based on the geothermal gradient but does not include any information on the potential type of geothermal resource. That is, the geothermal gradient data indicate that the subsurface temperature at a reasonable depth of about 2 km to 3 km would likely be sufficiently high to operate a geothermal power plant in areas that are ranked as having a medium to high geothermal favourability; however, more site specific exploration work would have to be conducted to determined if there is a suitable geothermal reservoir from which a sufficient volume of thermal water could be produced. If such a reservoir does not exist, there may still be the potential for the development of an enhanced geothermal system (also known as hot dry rock system).

5.7.2 Mackenzie Corridor

Another area of interest, which has been identified as having a medium geothermal favourability, is located in the Mackenzie Corridor in the areas of Deline, Tulita, Norman Wells, and Fort Good Hope (Figure 6). The geothermal anomaly in this area is mainly defined by temperature data from oil and gas exploration wells. The data coverage for this area is less dense compared to the southwestern part of the NWT. However, there is still enough data available to assess the geothermal regime on a large scale.

Based on existing data, the area seems to be less favourable than the Liard River and southern Mackenzie River basin. The borehole temperature data suggest that the geothermal gradient reaches values of about 45°C/km. Subsurface temperatures at 2 to 3 km depth can therefore be expected to be in the range of 90 to 135°C which would be sufficient for both district heating and geothermal power generation.

6.0 DATA GAP ANALYSIS AND RECOMMENDATIONS FOR FURTHER EXPLORATION

6.1 PHASED APPROACH TO GEOTHERMAL EXPLORATION AND RESOURCE DEVELOPMENT

Geothermal exploration and resource development usually follows a phased approach that is similar to the exploration and development of a mineral resource. A phased approach to geothermal exploration and development may consist of the following phases:

- Reconnaissance Study: The reconnaissance study is usually carried out on a regional scale (1,000s km^2) to identify potential targets for further, more-detailed geothermal exploration. Reconnaissance studies may include the review of any existing information that is useful for the assessment of the geothermal potential of the region of interest, air photo interpretation, remote sensing techniques, preliminary geological mapping, sampling of geothermal surface features (e.g., warm and hot springs, fumaroles, geysers etc.), and the development of a conceptual geothermal model.
- Pre-Feasibility Study: The pre-feasibility study is more focused (100s km^2) on specific target areas identified during the reconnaissance study. Exploration methods at the pre-feasibility level may include surface exploration for subsurface structure, detailed geological and hydrogeological mapping, low-level TIR flying, surface geophysics (i.e., gravity, magnetic, resistivity, seismic), advanced geochemistry, thermal gradient holes (DDH) with core logging, preliminary economical analysis, and environmental assessment and permitting considerations.
- Feasibility and Resource Confirmation: The feasibility study is a comprehensive study of a geothermal resource in which all geological, hydrogeological, engineering, legal, operating, economic, social, environmental and other relevant factors are considered in sufficient detail to serve as the basis for a final decision regarding the development of the geothermal resource. The feasibility study usually includes deep drilling and geophysical logging of the geothermal reservoir to support and refine the geothermal model. It also includes a quantitative assessment of the resource, detailed geochemical analysis of fluids, and the initiation of the formal environmental assessment and permitting process.
- Geothermal Resource Development: The development of a geothermal resource includes activities to bring the field to production, to complete the environmental assessment process, and to finalize legal, regulatory permits, and land arrangements. It also includes the drilling of the production and injection wells, testing of the wells, design and construction of the surface piping and fluid handling system.
- Power Plant Installation and Commissioning: The power plant installation and commissioning and the design and construction of the transmission line and supporting infrastructure are the final steps to supply electricity generated from the geothermal resource.

6.2 GEOLOGICAL DATA GAPS AND GEOLOGICAL APPROACHES TO GEOTHERMAL CHARACTERIZATION

This study focused on the assessment of the geothermal potential in the NWT on a territory-wide scale. Further geothermal exploration should be focused on specific areas that have been identified to likely possess an increased geothermal potential and are located in proximity to a community that could make use of this geothermal potential for heating and/or power generating purposes.

Further geological exploration of potential sites should include the compilation and review of all existing information for the specific area of interest and detailed geological mapping and structural analysis. The main objective of the detailed field geology in conjunction with geophysical exploration methods (see Section 6.3) is identifying appropriate sites for exploration drilling.

Exploration drilling provides the only possibility of collecting direct information on subsurface geology, structure, temperature, hydraulic properties, and water quantity and quality. A geothermal exploration drilling program should include the drilling of a number of thermal gradient holes, typically to depths of several hundred meters. The main purpose of the thermal gradient holes is to measure the local geothermal gradient and to assess the extent of the geothermal anomaly. In addition, the drill core will provide information on the geology and stratigraphy and core samples can be tested for thermal conductivity, porosity, and hydraulic conductivity. Furthermore, hydraulic in situ tests and water samples can yield additional information about hydraulic properties of the rock units, water quantity and water quality. Geochemical analyses of the water samples should include inorganic chemistry and geothermometry, stable isotopes (deuterium and O-18), and radioisotopes (tritium and radiocarbon). The stable isotopic composition of the water provides information on the origin of the water. Radioisotopes shed light on the subsurface residence time of the thermal water.

The geological, hydrogeological, and geophysical data collected during the geothermal exploration program should be used to develop a geothermal model that provides reliable information on the approximate depth and extent of the geothermal reservoir. This geothermal model can then be used to design a deep drilling program targeting the locations with the highest geothermal gradient and the reservoir formation with the highest hydraulic conductivity. The model would also be used to design the geothermal well field consisting of production and injection wells.

6.3 GEOPHYSICAL DATA GAPS AND GEOPHYSICAL APPROACHES TO GEOTHERMAL CHARACTERIZATION

Variable levels of coverage exist in the available geophysical data for the Northwest Territories. For reconnaissance surveys, only magnetic and gravity surveys have been conducted on a suitably widespread scale. Electrical data coverage is sparse, and other types of data more so.

For reconnaissance-level investigations of regions where geothermal resources are sought, extraction of the appropriate potential field data from NRCan would be a useful first step. The nature of anomalies sought depends on the expected geology of the region, so this exercise cannot be completed in isolation from other desk-top studies. Follow-up investigations conducted from the air should include electromagnetic surveys, with a wide range of possible targets (e.g. thermal alteration, elevated dissolved salts, increased levels of fluids, fracturing, clay layers, change in rock type), as described by Thanassoulas (1991).

Following identification of potentially appropriate sites and review of all geoscientific data, including any available information concerning heat flow, further geophysical surveys may be required to delineate the zone of interest and determine the source and reservoir characteristics. The exact nature of these investigations depends on the depth, extent and surface environment of the potential resource. The most likely appropriate techniques include terrestrial gravity, magnetic, electromagnetic (likely TEM) and electrical (resistivity soundings), and thermal mapping of the site, followed by targeted drilling and logging (to minimize cost and impact, while maximizing the potential for striking the centre of the resource). The range of combinations and permutations of these techniques is as varied as the geological situations in which a resource may be found; for a specific geological scenario it may be possible to develop a standard toolbox, routines and pricing for investigation, but for differing situations, the approach required may be entirely different. Examples of the process of using reconnaissance techniques followed by detail surveys have been provided by numerous authors, including Manzella (2008), Özgüler (1983), Spichak & Manzella (2008), and Thanassoulas (1991).

6.4 POTENTIAL TARGET AREAS FOR FURTHER GEOTHERMAL EXPLORATION

Potential target areas recommended for further geothermal exploration are primarily areas that were identified as having a medium to high geothermal potential (cf. Figure 6 and Sections 5.6 and 5.7). Further exploration should also be concentrated on areas that are situated in the vicinity of potential consumers for power and/or heat energy produced from a geothermal resource. Areas that fulfill both of these criteria are the larger communities in the southern Interior Platform, including the Fort Liard, Fort Simpson, Fort Providence, and Hay River areas. As mentioned above, Fort Liard, Fort Simpson, and Fort Providence may be of particular interest because these communities are currently relying on power produced by diesel generators at high costs whereas Hay River uses hydropower.

In addition to these communities in the southern NWT, the communities of Deline, Tulita, Norman Wells, and Fort Good Hope are also located in areas with an identified increased geothermal potential, although data coverage in this region is sparse and geothermal gradients tend to be lower compared to the southern Interior Platform. However, a more localized study incorporating all available information may yield some further insight into the geothermal potential of this area.

6.5 RECOMMENDATIONS FOR FURTHER GEOTHERMAL EXPLORATION

The existing temperature data from deep oil and gas exploration boreholes within the Interior Platform is a very valuable set of data to estimate the geothermal potential on a large scale. Other regions with less data coverage are mostly either remote and of no immediate interest for possible geothermal development or in geological settings that are not considered favourable for geothermal potential, e.g., the Canadian Shield.

EBA recommends that further geothermal exploration efforts be focused on the areas described in Section 5.7 that were identified as having medium to high geothermal potential mainly based on temperature data from deep oil and gas exploration boreholes. Next exploration steps may include geothermal desktop studies at a more local scale in favourable areas situated in close proximity to larger communities. These studies should include a thorough review of all existing data (geology, hydrogeology, geochemistry, geophysics etc.) for the particular area of interest. Data gaps should be filled by using surface and, at a later stage, subsurface exploration techniques. The geothermal exploration should follow a phased approach, such as described in Section 6.1. The exploration strategy should be tailored to the specific site conditions and should be regularly reviewed and adjusted based on exploration results at different milestones.

Table 5 shows a generic cost estimate for a geothermal pre-feasibility study. This cost estimate is very approximate and cannot be applied to a specific project without adjustment. Typical timelines for geothermal exploration from early reconnaissance to a pre-feasibility study are likely in the range of 1-5 years, depending on specific circumstances (site conditions, size of study area footprint, existing data, type of geothermal development, depth and extent of geothermal resource, existing infrastructure, financing etc.).

TABLE 5: GENERIC COST ESTIMATE FOR GEOTHERMAL PRE-FEASIBILITY STUDY

Task	Estimated Cost Range		
Existing information review	$20,000	–	$30,000
Detailed field geology	$30,000	–	$40,000
Geophysical surveys	$40,000	–	$60,000
Thermal gradient holes	$200,000	–	$250,000
Borehole geophysics and well temperature survey	$20,000	–	$30,000
Core logging and core sample analyses	$20,000	–	$30,000
Hydrogeology and hydrogeochemistry	$20,000	–	$30,000
Conceptual geothermal model	$20,000	–	$30,000
Preliminary economical evaluation	$10,000	–	$20,000
Preliminary environmental assessment and permitting	$20,000	–	$30000
TOTAL	$400,000	–	$550,000

7.0 CONCLUSIONS

EBA has compiled existing information that is relevant with respect to the evaluation of the geothermal potential in the NWT on a territory-wide scale. The most relevant existing information regarding geothermal potential is temperature data from oil and gas exploration boreholes within the Interior Platform (Western Canadian Sedimentary Basin). Other regions, such as large portions of the Cordillera, the Canadian Shield and the Arctic Platform lack the direct geothermal gradient data available in the WCSB. In theses areas, general geological information, seismicity data, and proximity to known warm and hot springs were used to estimate the geothermal favourability.

The compiled data that were in a suitable format to be included into a GIS database were used to build an ArcGIS database for visualization and analysis of the information. This database was then used to create a geothermal favourability map of the NWT.

The main conclusions of this desktop study can be summarized as follows:

- The existing geothermal-related information in the NWT is rather irregularly distributed. There is reasonable coverage of some areas, mainly within the WCSB, with respect to subsurface temperature data from oil and gas exploration wells whereas data in other areas is very sparse.
- The geothermal favourability mapping identified two main areas with increased geothermal potential:
  - The southern portion of the WCSB in the southwest corner of the NWT including the larger communities of Fort Liard, Fort Simpson, Fort Providence, and Hay River (medium-high to high geothermal potential). The geothermal gradient in this area exceeds values of 60°C/km so that temperatures > 100°C can be expected at reasonable depth of about 2 km or even less.
  - The central part of the WCSB, including the communities of Deline, Tulita, Norman Wells, and Fort Good Hope (medium geothermal potential), also shows a geothermal anomaly but less pronounced compared to the southern portion. The maximum geothermal gradient in this area appears to be in the range of 40°C/km to 50°C/km.
- The Favourability Map indicates a few additional areas within the Cordillera that are identified as having a medium geothermal potential. However, the existing data for the Cordillera are very sparse and collection of additional data is required to better define the geothermal potential in these areas.
- More advanced geothermal exploration should primarily be focused on areas with an identified medium to high geothermal potential and those areas that are located within a reasonable distance of potential energy consumers.

8.0 LIMITATIONS OF REPORT

This report and its contents are intended for the sole use of Government of the Northwest Territories (GNWT) and their agents. EBA does not accept any responsibility for the accuracy of any of the data, the analysis or the recommendations contained or referenced in the report when the report is used or relied upon by any Party other than GNWT, or for any Project other than the proposed development at the subject site. Any such unauthorized use of this report is at the sole risk of the user. EBA's General Conditions are provided in Appendix A of this report.

9.0 CLOSURE

We trust this report meets your present requirements. Should you have any questions or comments, please contact the undersigned at your convenience.

Respectfully submitted,

EBA Engineering Consultants Ltd.

Stephan Klump, Dipl.-Geol., Ph.D.
Hydrogeologist, Team Lead
Whitehorse Environment Group
Direct Line: (867) 668-2071 ext.250
Email: sklump@eba.ca

Sarah Sternbergh, EIT
Junior Hydrogeologist
Whitehorse Environment Group
Direct Line: 867.668.2071 x253
Email: ssternbergh@eba.ca

Jack T. Dennett, P.Geol. (NWT)
Senior Project Geoscientist
Arctic Engineering Group
Direct Line: (867) 668-2071 ext.230
Email: jdennett@eba.ca

REFERENCES

Blackwell, D.D. and Richards, M. (2004) Geothermal Map of North America. Am. Assoc. Petrol. Geol., 1 map sheet, 1:6,500,000.

Bleeker, W., and Hall, B., (2007) The Slave Craton: Geology and metallogenic evolution, in Goodfellow, W.D., ed., Mineral Deposits of Canada: A Sythesis of Major Deposit Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 849-879.

Blewitt, G., Coolbaugh, M., Holt, W., Kreemer, C., Davis, J.L., and Bennett, R.A. (2002) Targeting of Potential Geothermal Resources in the Great Basin from Regional Relationships Between Geodetic Strain and Geological Structures, Published by GRC Transactions (2002), accessed online Feb 2010.

Blodgett, L. and Slack, K. (2009) Geothermal 101: Basics of Geothermal Energy Production and Use. Geothermal Energy Association. Washington, D.C.

Bostock, H.H.,(1980), Geology of the Itchen Lake Area, District of Mackenzie, Geological Survey of Canada Memoir 391, Energy, Mines and Resources Canada

Canada's National Lithoprobe Goescience Project, http://www.lithoprobe.ca/transects/snorcle/, accessed February 18, 2010.

Cook, F.A., van der Velden, A.J., Hall, K.W., Roberts, B.J. (1998) Tectonic delamination and subcrustal imbrication of the Precambrian lithosphere in northwestern Canada mapped by LITHOPROBE, Geology, v. 26; no. 9; p. 839-842

Coolbaugh, M.F., Taranik., J.V., Raines, G.L., Shevenell, L.A., Sawatzky, R..B., and Minor, T.B. (2002) A Geothermal GIS for Nevada: Defining Regional Controls and Favourable Exploration Terrains for Extensional Geothermal System

Crandall, J.T. and Sadlier-Brown, T.L. (1976) Data on geothermal areas Cordilleran Yukon, Northwest Territories, and adjacent British Columbia, Canada. Energy, Mines and Resources Canada, Earth Physics Branch, Open File Report No. 78-1, 23 p.

Diaz-Gonzalez, L. and E. Santoyo (2008) A New Precise Calibration of the Na/K Geothermometer using a World Database of Geothermal Fluids and Improved Geochemometric Techniques. Abstract from 2008 Goldschmidt Conference, P.A215.

Frith, R. A., (1993), Precambrian Geology of the Indin Lake Map Area, District of Mackenzie, Northwest Territories, Geological Survey of Canada Memoir 424, Energy, Mines and Resources Canada

Fournier, R.O. (1981) Application of Water Geochemistry to Geothermal Exploration and Reservoir Engineering. Chapter 4 in Geothermal Systems: Principles and Case Histories, L. Ryback and L.J.P. Muffler, eds., Wiley Publishing, NY, pp.109-143.

Fournier, R.O. and Truesdell, A.H. (1973) An Emperical Na-K-Ca Geothermometer for Natural Waters. Geochim. Cosmochim. Acta, vol. 37, pp. 1255-1275.

Gabrielse, H., Monger, J.W.H., Wheeler, J.O., and Yorath, C.J. (1991); Part A. Morphological belts, tectonic assemblages, and terranes; in Chapter 2 of Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C.J. Yorath (ed.); Geological Survey of Canada, Geology of Canada, no. 4, p. 15-28

Gabrielse, H., Blusson, S.L., Roddick, J.A., (1973) Geology of Flat River, Glacial Lake and Wrigley Lake Map-Areas, District of Mackenzie and Yukon Territory, Geological Survey of Canada Memoir 366, Department of Energy, Mines and Resouces, Ottawa Canada

Garchar, L. and G. Arehart (2008) Origin and Characterization of Geothermal Waters at Desert Queen, Nevada. GRC Transactions, Vol. 32, pp.147-151.

Ghomshei, Mory (2009), Fort Simpson Geothermal Potential for Cogeneration of Power and Heat (draft report)

Gordey, S.P. and Anderson, R.G., Evolution of the Northern Cordilleran Miogeocline, Nahanni Map Area (105I), Yukon and Northwest Territories, Geological Survey of Canada Memoir 428, Energy, Mines and Resources, Canada

Grasby, S.E., Majorowicz, J., and Ko, M. (2009) Geothermal Maps of Canada, Geological Survey of Canada Open File 6167, Natural Resources, Canada

Greenwood, H. J., Woodsworth, G. J., Read, P. B., Ghent, E. D., and Evenchick, C. A. (1991), Metamorphism, Chapter 16 in Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C. J. Yorath, (ed.); Geological Survey of Canada, Geology of Canada, no. 4, p. 533 go 570

Henderson, J.B., (1985), Geology of the Yellowknife-Hearne Lake Area, District of Mackenzie: A Segment Across an Archean Basin, Geological Survey of Canada Memoir 414

Hoffman, P.F. (1990) Subdivision of the Churchill Province and extent of the Trans-Hudson Orogen, in Lewry, J.F., and Stauffer, M.R., eds., The Early Proterozoic Trans-Hudson Orogen of North America: Geological Association of Canada, Special Paper 37, p. 15-39.

Hume, G.S., (1954), The Lower Mackenzie River Area, Northwest Territories and Yukon, Geological Survey of Canada Memoir 273, Canada Department of Mines and Technical Surveys

Jessop, A.M. (2008) Review of National Geothermal Energy Program. Phase 1 – Geothermal Potential of Sedimentary Basins. Geological Survey of Canada, Open File 5690, 155 p.

Jessop, A.M. (2008) Review of National Geothermal Energy Program. Phase 2 – Geothermal Potential of the Cordillera. Geological Survey of Canada, Open File 5906, 88 p.

Kearey, P., Brooks, M. & Hill, I. (2002) An Introduction To Geophysical Exploration, 3rd Ed. Ix + 262 Pp. Oxford: Blackwell Science.

Kidd, D.F., (1936), Rae to Great Bear Lake, Mackenzie District, N.W.T., Geological Survey of Canada Memoir 187, Canada Department of Mines

Lewis, T.J., Hyndman, R.D., Flück, P. (2003) Heat flow, heat generation, and crustal temperatures in the Northern Canadian Cordillera: Thermal Control of Tectonics, Journal of Geophysical Research, v. 108, no. B6, 2316, doi. 10.1029/2002JB002090

MacLean, B.C. and D.W. Morrow (2004) Bovie Structure: its evolution and regional context, Bulletin of Canadian Petroleum Geology, Vol. 52, No. 4; p 302-324.

Majorowicz, J.A., Jessop, A.M., Lane, L.S. (2005) Regional heat flow pattern and lithospheric geotherms in northeastern British Columbia and adjacent Northwest Territories, Canada. Bulletin of Canadian Petroleum Geology, 53(1), 51-66.

Majorowicz, J. A. and Morrow, D. W. (1998) Subsurface Temperature and Heat Flow – Yukon and Northwest Territories, Geological Survey of Canada Open File 3626

Majorowicz, J.A. (1996) Anomalous heat flow regime in the western margin of the North American Craton, Canada. J. Geodynamics, 21(2), 123-140.

Manzella, A. (2008) Geophysical Methods in Geothermal Exploration. Italian National Research Council. Workshop on Geothermal energy: resources and technology for a sustainable development. ICS-UNIDO, 10-12 December 2008, Trieste, Italy, 40 p.

Noorollahi, Y., Itoi, R., Funjii, H., Tanaka, T. (2007) Elsevier Computers and Geosciences, v. 33, Iss. 8, ISSN 0098-3004.

Parish, R. R., (1991), Precambrian basement rocks of the Canadian Cordillera, Chapter 4 in Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C. J. Yorath (ed.); Geological Survey of Canada, Geology of Canada, no. 4, p. 87-96)

Price, R. A. (1994) Cordilleran Tectonics and the Evolution of the Western Canadian Sedimentary Basin, Chapter 2 in Geological Atlas of the Western Canada Sedimentary Basin, G.D. Mossop and I. Shetsen (comp.), Canadian Society of Petroleum Geologists and Alberta Research Council, Special Report 4, URL <http://www.ags.gov.ab.ca/publications/wcsb_atlas/atlas.html>, [February 23, 2010].

Özgüler, M.E., Turgay, M.I. and Şahin, H (1983) Geophysical Investigations In Denizli Geothermal Fields, Turkey. Bulletin Of The Mineral Research And Exploration Institute Of Turkey, October 1982-April 1983 99/100. p88-99.

Souther, J. G., (1991), Volcanic Regimes, Chapter 14 in Geology of the Cordilleran Orogeny of Canada, H. Gabrielse and C.J. Yorath (ed.); Geological Survey of Canada,Geology of Canada, no. 4, p. 457 to 490

Spichak, V., & Manzella, A. (2008) Electromagnetic Sounding of Geothermal Zones. Journal of Applied Geophysics 68, 459-478.

Thanassoulas, C. (1991) Geothermal Exploration Using Electrical methods. Geoexploration 27, p321-350.

Trettin, H. P., ed. (1991) Geology of the Innuitian Orogen and Arctic platform of Canada and Greenland. GSC.

Verma, S.P. and Santoyo, E. (1995) New Improved Equations for Na/K and SiO2 Geothermometers by Error Propagation. Proceedings of World Geothermal Congress, 1995, p.963-968.

Walsh, W., Hersi, O.S., Hayes, M. (2005) Liard Basin – Middle Devonian Exploration in Summary of Activities 2005, BC Ministry of Energy and Mines, p. 38-41

Ward, S.H. (1975) Geophysical Methods Applied to Detection, Delineation and Evaluation of Geothermal Resources. University of Utah. 106 p.

Woodsworth, G. J., Anderson, R. G., and Armstrong, R. L. (1991), Plutonic Regimes, Chapter 15 in Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C.J. Yorath (ed.); Geological Survey of Canada, Geology of Canada, no. 4, p. 491-531

Yorath, C. J., Gordy, P. L., Williams, G. K., Bustin, R. M., Bell, R. T., Souther, J. G., and Halstead, E.C. (1991) Chapter 20 in Geology if the Canadian Cordillera, H. Gabriesle and C. J. Yorath (ed.); Geological Survey of Canada no. 4, p. 769-801

TABLES

TABLE 1: EXISTING GEOTHERMAL-RELATED INFORMATION FOR THE NWT

Publication Type	Date	Title	Author (s)	Publisher/Organization	Additional Information
Report					
	2008	Review of National Geothermal Energy Program Phase 2 - Geothermal Potential of Cordillera	Jessop	Geological Survey of Canada	Open file 5906
	2009	Fort Simpson Geothermal Potential for Cogeneration of Power and Heat	Ghomshei	University of British Columbia NBK Institute of Mining Engineering	-
	2005	Geoelectric Structure of the Proterozoic Wopmay Orogen and adjacent terranes, Northwest Territories, Canada	Wu, Fergusun and Jones	Canadian Journal of Earth Sciences	Issue 42, p 955-981, doi. 10.1139/E05-042
	2009	Comments for the NWT Electricity Review	Robinson	Arctic Energy Alliance (AEA)	
	2005	Chapter 30 - Geothermal Regime in the Western Canadian Sedimentary Basin	Bach and Burwash	Canadian Society of Petroleum Geologists and Alberta Research Council	*in* Geological Atlas of Western Canada
	2005	Liard Basin - Middle Devonian Exploration	Walsh et. al.	BC Ministry of Energy and Mines	-
	2003	Interpretations of Precambrian basement based on recent aeromagnetic data, Mackenzie Valley, Northwest Territories	Alsper, et. al	NRCan, Geological Survey of Canada	-
	-	Groundwater in the Permafrost Regions of the Yukon, Northern Cordillera and Mackenzie District	Brandon	Geological Survey of Canada	-
	2003	Lithospheric Structure beneath the Archean Slave Province and Proterozoic Wopmay orogen, northwestern Canada, from a LITHOPROBE refraction_wide-angle relflection survey	Viejo and Clowes	Geophysics Journal International	Royal Astronomical Society, Provided by the NASA Astrophysics Data System
	2005	Current Tectonics of the Northern Canadian Cordillera	Hyndman, et. al.	Canadian Journal of Earth Sciences	-
	2003	Heat flow, heat generation, and crustal temperatures in the northern Canadian cordillera: Thermal control of tectonics	Lewis et. al.	Journal of Geophysical Research	Vol. 108, NO> B^, 2316, doi. 10.1029/2002JB002090
	2005	Regional heat flow pattern and lithospheric geotherms in northeastern British Columbia and adjacent Northwest Territories, Canada	Majorowicz et. al.	Bulletin of Canadian Petroleum Geology	Vol. 53, NO. 1 (March 2005), P. 51-66
	2008	Spring water trace element geochemistry: A tool for resource assesment and reconnaissance mineral exploration	Caron, et.al.	Applied Geochemistry 23	Applied Geochemistry 23 (2008) 3561-3578
	1984	Terrestrial Heat Flow in Canada	Jessop, et. al.	Tectonophysics	Vol. 103 Issues 1-4, 20 March 1984, Pages 239-261, Terrestrial Heat Flow Studies and the Structure of the Lithosphere
	2004	Bovie Structure: its evolution on regional context	MacLean and Morrow	Bulletin of Canadian Petroleum Geology	Vol. 52, No.4 (December 2004), P. 302-324
	1996	Anomalous Heat Flow Regime in the Western Margin of the North American Craton, Canada	Majorowicz, J. A.	Journal of Geodynamics	Vol. 21, No. 2, pp. 123-140, 1996, Elsvier Science, Ltd. Printed in Great Britain
	2008	Characterizing the shale gas resource potential of Devonian-Mississippian strata in Western Canadian sedimentary basin: Application of and integrated formation evaluation	Ross and Bustin	AAPG Bulletin	v. 92, No. 1 (January 2008), pp. 87-125
	1973	Geology of Flat River, Glacier Lake and Wringly Lake Areas (NWT)	Gabrielse, Blusson, and Roddick	GSC	Geological Survey of Canada Memior 366
	1992	Geology of the Cordilleran Orogeny	Gabrielse and Yorath	GSC	Geology of Canada no. 4 - Several Chapters
	1975	Geology of the Lower Paleozoic Formations in the Subsurface of the Fort Simpson Area, District of Mackenzie, N.W.T.	Meijer-Drees	GSC, Energy Mines and Resources Canada	Geological Survey Paper 74-40
	1976	Geothermal Energy from Sedimentary Basins	Jessop	Geothermal Service of Canada, EMRC	Geothermal Series Number 8
	1978	Arctic Geophysical Review: Heat Flow North of 60 (pp. 25 - 33	Judge and Jessop	Publications of the Earth Physics Branch	Volume 45, No. 4
	1976	Report on Study of Geothermal Resources in Western Canadian Sedimentary Basins from Existing Data - Phase One	Sproule and Associates	Geothermal Service of Canada, EMRC	Earth Physics Branch Open File No. 77-13
	1983	Subsurface Temperature Data from Arctic Wells	Geotech Engineering	Geothermal Services of Canada (EMRC Earth Physics Branch)	Earth Physics Branch - Open File Number 83-11
	1954	The Lower Mackenzie River Area, Northwest Territories and Yukon	Hume	Canada Department of Mines and Technical Surveys	Canada Geological Survey Memoir 273
	1936	Rae to Great Bear Lake Mackenzie District, N.W.T	Kidd	Canada Department of Mines	Bureau of Economic Geology Geological Survey Memoir 187
	1993	Precambrian Geology of the Indin Lake Map Area, District of Mackenzie, Northwest Territories	Frith	Energy, Mines and Resouces Canada	Geological Survey of Canada Memoir 424
	1980	Geology of the Itchen Lake Area, District of Mackenzie	Bostock	Energy, Mines and Resouces Canada	Geological Survey of Canada Memoir 391
	1985	Geology of the Yellowknife-Hearne Lake Area, District of Mackenzie: A Segment Across an Archean Basin	Henderson	Geological Survey of Canada	Geological Survey of Canada Memoir 414
	1993	Evolution of the Northern Cordilleran Miogeocline, Nahanni Map Area (105I), Yukon and Northwest Territories	Gordey and Anderson	Energy, Mines and Resouces Canada	Geological Survey of Canada, Memoir 428
	1978	Hotsprings of Western Canada: A Complete Guide	McDonald, Pollack and MacDermot	Labrador Tea Company	-
	1974	Canadian Geothermal Data Collection - Northern Wells, 1955 to February 1974	Taylor and Judge	Geothermal Service of Canada, Earth Physics Branch	Department of Energy Mines and Resouces
	1975	Canadian Geothermal Data Collection - Northern Wells 1975	Taylor and Judge	Energy Mines and Reasources Earth Physics Branch	Geothermal Series Number 6
	1978-80	Canadian Geothermal Data Collection - Northern Wells 1978-80	Judge, et. al.	Goethermal Service of Canada, Energy Mines and Resouces Earth Physics Branch	Geothermal Series Number 12
	1994	Cordilleran Tectonics and the Evolution of the Western Canadian Sedimentary Basin	Price	Canadian Society of Petroleum Geologists and Alberta Research Council	Chapter 2 *in* Geological Atlas of the Western Canadian Sedimentary Basin
	2007	The Slave Craton: Geology and metallogenic evolution	Bleeker abd Hall	Geologial Association of Canada, Mineral Deposits Division	*in* Mineral Deposits of Canada: A Synthesis of Major Deposit Types
	1990	Subdivision of the Churchill Province and extent of the Trans-Hudson Orogen	Hoffman	Geological Association of Canada	*in* The Early Proterozoic Trans-Hudson Orogen of North America: Geological Association of Canada, Special Paper 37

TABLE 1: EXISTING GEOTHERMAL-RELATED INFORMATION FOR THE NWT					
Publication Type	Date	Title	Author (s)	Publisher/Organization	Additional Information
	1998	Tectonic delamination and subcrustal imbrication of the Precambrian lithosphere in northwestern Canada mapped by LITHOPROBE	Cook, van der Velden, Hall, and Roberts	Geology	v.26, no. 9, p. 839-842
	2007	GIS model for geothermal resource exploration in Akita and Iwate prefractures, northern Japan	Noorollahi et. al.	Elsevier, Computers and Geosciences	v. 33, I. 8
	2002	Targeting of potential geotheraml resouces in the great basin from regional relationships between geodetic strain and geological structures	Blewitt et. al.	GRC Trasactions	-
	1998	Subsurface Temperature and Heat Flow - Yukon and Northwest Territories	Majorowicz and Morrow	Geological Survey of Canada	Open File 3626
	2002	A Geothermal GIS for Nevada: Defining Regional Controls and Favourable Exploration Terrains for Extensional Geothermal System	Coolbaugh et. al.		-
	2001	The Great Slave Lake Shear Zone - Implications for Exploration in NW Alberta and NE BC	Peirce et. al.		-
	1994	Chapter 3 - Structure and Architecture of the Western Canada Sedimentary Basin	Wright et. al.	Canadian Society of Petroleum Geologists and Alberta Research Council	*in* Geological Atlas of the Western Canadian Sedimentary Basin
	-	Probing the Lithosphere of the Wopmy Orogen	Cook		Presentation summary
	1994	Cordilleran Tectonics and the Evolution of the Western Canadian Sedimentary Basin	Price	Canadian Society of Petroleum Geologists and Alberta Research Council	*in* Geological Atlas of the Western Canadian Sedimentary Basin
	-	Evolution of thought on the Evolution of a Craton: New Perspectives on the Origin and Reworking of the Western Churchill Province	Pehrsson et. al.	Geological Survey of Canada	-
	1976	Yukon-NWT Geothermal Study	Nevin Sadlier-Brown Geological Consultants	Energy Mines and Resources	Includes location maps, water chemistry plots etc.
Map					
	2004	Geothermal Map of North America	Blackwell and Richards	American Association of Petroleum Geologists	-
	2009	Geothermal Maps of Canada	Grasby, Majorowicz, and Ko	Geological Survey of Canada	Open file 6167 (25 maps)
	1994	Canada Seismicity Map	-	Energy Mines and Resources	The National Atlas of Canada 5th Edition
	2000	Canada Gravity Anomally Map	Miles, et. al	Geological Survey of Canada, NRCan	Open File 3830a
	1991	Metamorphic map of the Canadian Cordillera	Reed et. al	Geological Survey of Canada	Map No. 1714A
	1991	Tectonic Assemblage Map of the Canadian Cordillera	Wheeler and McFeely	Geological Survey of Canada	Map No. 1712A
	2004	Seismic and Well Database Map	-	Geological Survey of Canada, Energy Mines and Resources	GSC Bulletin 575
	1970	Physiographic Regions of Canada	-	Geological Survey of Canada	-
	1982	Magnetic Anomally Map of Arctic Canada	-	Geological Survey of Canada, NRCan	Map 1512A
	2000	Magnetic Anomally Map of Canada	-	Geological Survey of Canada, NRCan	Map 3829A
	2005	Radioactivity Map of Canada	-	Geological Survey of Canada, NRCan	Open File 4756
		NWT Energy Map (Infrastructure Locations)		Centre for Energy, NWT	-
		Fort Simpson Area Aeromagnetic Map	Petrel Robertson Consulting		-
	1965	Geology of Flat River, Glacier Lake and Wrigley Lake Areas (NWT)	Gabrielse, Roddick and Blusson	GSC	-
	2009	Locations of Known Hot and Warm Springs in the NWT	-	Northwest Territories Protected Areas Strategy	Temperature Data and GPS Locations included in Data Compilations
	1996	Geological Atlas of the Beufort Mackenzie Area - Geothermal Gradients	Dixon	GSC	Miscelaneous Report 59
		BC Geothermal Potential Map		BC Ministy of EMPR	for reference
	1992	Geothermal Resouces of British Columbia	Fairbank and Faulkner	BC Ministy of EMPR	GSC Open File 2526
	1997	Terranes and Tectonic Elements of Northwestern North America		SNORCLE	-
	2005	NWT_Explorers Map	-	Government fo NWT Deptarment if Industry, Tourism and Investment	-
	1993	Slave Craton and Environs	-	Geological Survey of Canada, NRCan	open file 2559
	2009	Wrigley NWT Surficial Geology Map	-	Geological Survey of Canada, NRCan	95O/NW (1:100,000), Open File 5835
	1982	Yukon Coastal Plain - Quaternary Geology	Rampton	Geological Survey of Canada	Map 1503A
	1980	Banks Island, NWT Surficial Geology Map	-	Geological Survey of Canada	Map 16-1979
Presentation					
	2009	A Niche for Geothermal Energy in Canada	Yang	Borealis GeoPower	-
		The Business of Geothermal Energy	Dunn	Canadian Geothermal Energy Association	Geothermal 101 - Community Workshop
		Exploration to Development	Dunn	Canadian Geothermal Energy Association	Geothermal 101 - Community Workshop
		Geothermal Energy Workshop	Yang	Canadian Geothermal Energy Association	Geothermal 101 - Community Workshop
		Geothermal Energy in Fort Simpson, NWT	Dunn	Canadian Geothermal Energy Association	Geothermal 101 - Community Workshop
		The Business of Geothermal Energy	Dunn	Canadian Geothermal Energy Association	Geothermal 101 - Community Workshop
	2009	Borealis - Geothermal Energy	Yang	Borealis GeoPower	-
Data Compilation					
	2008	Review of National Geothermal Energy Program Phase 1 - Geothermal Energy Potential of Sedimentary Basins	Jessop	Geological Survey of Canada	Open File 5690
	2005	The Canadian Geothermal Data Compilation	Jessop et. al.	Geological Survey of Canada	Open File 4887
	1976	Canadian Geothermal Data Collection - Northern Wells 1975	Taylor and Judge	Geothermal Service of Canada	-
	1982	Canadian Geothermal Data Collection - Northern Wells 1981	Taylor, et. al.	Geothermal Service of Canada	Geothermal Series Number 13
	1979	Canadian Geothermal Data Collection - Northern Wells 1977-1978	Judge, Taylor and Burgess	Goethermal Service of Canada	Geothermal Series Number 11
	1975	Canadian Geothermal Data Collection - Northern Wells 1974	Taylor and Judge	Geothermal Service of Canada	Geothermal Series Number 3
	1977	Canadian Geothermal Data Collection - Northern Wells 1976-1977	Taylor and Judge	Geothermal Service of Canada	Geothermal Series Number 10
	2008	Seismic Hazard Epicentre File	-	NRCan	-
	2009	Hot and Warm Springs of the NWT	-	NWT Protected Areas Strategy	Compiled by PAS from a number of sources
	2008	NWT Community Power Sources	NWT Electricity Review	Government of NWT	-

TABLE 1: EXISTING GEOTHERMAL-RELATED INFORMATION FOR THE NWT					
Publication Type	Date	Title	Author (s)	Publisher/Organization	Additional Information
	2006	NWT Community Populations	-	Statistics Canada	Compiled from Statistics Canada
Websites					
	-	Permafrost - Canadian Geothermal Data Collection	-	Geological Survey of Canada	http://cgc.rncan.gc.ca/permafrost/geothermal_background_e.php
	-	NTGO - Northwest Territories Geosciences Office	-		http://www.nwtgeoscience.ca/services/#two
	-	The Canadian Geothermal Data Collection Description of Data Files	-		http://nsidc.org/data/docs/fgdc/ggd503_boreholes_ncanada/data.html
	-	National Energy Board - Released Information Summary	-		http://www.neb.gc.ca/clf-nsi/rthnb/nrthffshr/pblctnrprt/frntrlndsrlsdnf2005-eng.pdf
	-	National Snow and Ice Centre FTP Site - well data	-		ftp://sidads.colorado.edu/pub/DATASETS/fgdc/ggd503_boreholes_ncanada/
	-	LITHOPROBE Transects	-	SNORCLE	-
	-	SNORCLE Line 1 Interpretation	-	SNORCLE	-

Table 2: Digital Aerial Geophysical Data Availability From Natural Resources Canada											
Project No.	Project Name/ Sub-Area Name	Year Flown	Survey Type	Altitude	Line Spacing	Line Direction	Survey Km	General Location			
								South Lat.	North Lat.	East Long.	West Long.
11900	DARNLEY BAY	1973	TF	610 m BAR	2000 m	N, S	4 023	68 40'	69 47'	122 45'	124 37'
15400	TATHLINA LAKE	1969-71	TF	-	-	-	18 830	-	-	-	-
15401	762 m BAR Area	1969-71	TF	762 m BAR	300 m	N, S	12 552	60 00'	60 30'	116 00'	117 00'
15402	1219 m BAR Area	1969-71	TF	1219 m BAR	300 m	N, S	6 278	60 00'	60 15'	117 00'	118 00'
16600	BAFFIN ISLAND	1984	TF	-	-	-	64 048	-	-	-	-
16601	305m MTC Block	1984	TF	305 m MTC	1000 m	N, S	56 404	72 00'	73 54'	80 00'	90 06'
16602	1524 m BAR Block	1984	TF	1524 m BAR	1500 m	N, S	5 746	73 00'	73 46'	80 52'	83 30'
16603	1828 m BAR Block	1984	TF	1829 m BAR	1500 m	N, S	1 898	73 00'	73 46'	80 00'	80 53'
16800	BEAUFORT SEA AND YUKON	1985	TF	-	-	-	82 000	-	-	-	-
16801	Yukon (2km N-S)	1985	TF	1829 m BAR	2000 m	N, S	15 238	68 00'	69 40'	135 00'	141 00'
16802	Beaufort (6km NE-SW)	1985	TF	305 m BAR	6000 m	NE, SW	9 753	71 00'	72 00'	132 00'	142 00'
16803	Beaufort (2km NE-SW)	1985	TF	305 m BAR	2000 m	NE, SW	31 902	68 45'	71 00'	132 00'	142 00'
16804	Beaufort (2km NW-SE)	1985	TF	305 m BAR	2000 m	NW, SE	25 127	69 15'	72 00'	126 00'	135 00'
20200	WHITEHILLS	1988	TF VG VLF	150 m MTC	300 m	NW, SE	6 855	64 30'	65 05'	95 45'	96 30'
21000	LINCOLN SEA (1988/91)	1988-91	TF	305 m BAR	4000 m	N, S	24 000	81 48'	84 25'	43 20'	72 00'

TF	Magnetic Total Field
VG	Measured Vertical Gradient of the Total Field
EM	Electromagnetic
VLF	Very Low Frequency EM
TDEM	Time Domain EM
FDEM	Frequency Domain EM
MTC	Mean Terrain Clearance
BAR	Barometric

TABLE 3: HOT AND WARM SPRINGS IN THE NORTHWEST TERRITORIES

Spring	Location		Est. Discharge Total System	Max. Temp.	Hydrogeochemistry						Geothermometer		
	Lat	Long			Na	K	Ca	Mg	SiO2	B[1]	Na-K-Ca[1]	Na-K[2]	SiO_2[3]
			(L/s)	(°C)	mg/L					-	°C		
West Cantung	61.92	128.25	30	41	47	1.24	7.6	1.2	58	0.33	108	84	109
East Cantung	61.92	128.25	-	29	64	1.36	3.6	0.5	68	0.33	108	70	117
Ekwi	64.05	128.25	30	46	5850	80	260	66	54	0.33	122	46	106
Deca East	64.17	128.42	7	22	420	6.2	285	65	38	0.33	91	50	90
Deca West	64.17	128.47	<2	16	200	3.64	155	58.8	34	0.33	94	62	85
Mountain 1	64.53	129.25	15	10	80	1.6	350	102	34	0.33	82	67	85
Mountain 2	64.52	129.25	<3	10	82	1.6	390	112	34	0.33	81	66	85
Mountain 3	64.63	129.22	25	9	2.8	0.7	270	60	34	0.33	138	319	85
North Redstone	63.72	126.42	<1	9	12.4	0.92	39	34.5	40	0.33	121	163	92
Grizzly Bear	62.67	127.92	30	44	22	23.8	105	25.5	54	0.33	275	766	106
Nahanni Headwater	62.82	128.83	60	64	56	1.68	2.8	0	109	0.33	122	92	142
South Redstone	63.40	125.87	120	54	49	1.46	72	21	58	0.33	99	91	109
Redstone Jct 1	63.53	125.70	25	15	88.5	2.54	88	34.1	47	0.33	104	89	100
Redstone Jct 2	63.55	125.73	4	8	5.3	0.48	69	35.2	31	0.33	114	183	82
North Cantung	62.12	128.42	5	32	0.8	0.7	19	12.9	21	0.33	204	664	66
Nahanni North	62.37	128.67	40	58	67	1.36	1.9	0	78	0.33	111	68	124
Broken Skull	62.75	128.13	35	45	52	33.8	140	50.2	56	0.33	254	550	108
Wild Mint	61.42	126.58	50	29	1.4	2.54	125	25.5	45	0.33	243	1143	98
Rabbitkettle	61.95	127.18	<2	21	3.85	4.84	200	39.8	40	0.33	236	853	92
Hole-in-the-Wall	61.70	127.28	30	47	28	0.7	1.2	0	83	0.33	111	80	127
Flat Fruit	61.67	127.58	<3	11	24	5.98	470	49	43	0.33	167	319	96
Cache Creek Cabin	64.65	129.21	-	-	-	-	-	-	-	-	-	-	-
Carcajou R / Magel Lake	65.28	127.75	-	-	-	-	-	-	-	-	-	-	-
Godlin	64.06	128.24	-	-	-	-	-	-	-	-	-	-	-
Hoosier Ridge pond	65.38	127.57	-	-	-	-	-	-	-	-	-	-	-
Kraus (Clausen Creek)	61.25	124.06	-	37	-	-	-	-	-	-	-	-	-
Lymnae	64.15	128.43	-	21	-	-	-	-	-	-	-	-	-
Meilleur	61.13	124.90	-	-	-	-	-	-	-	-	-	-	-
Moonscape	64.53	129.25	-	11	-	-	-	-	-	-	-	-	-
Moore's	62.34	128.13	-	40	-	-	-	-	-	-	-	-	-
Mountain River/Gayna R	65.42	129.12	-	-	-	-	-	-	-	-	-	-	-
North Cantung	62.12	128.42	-	32	-	-	-	-	-	-	-	-	-
Roche-qui-trempe-α-l'eau	63.30	123.62	-	31	-	-	-	-	-	-	-	-	-
Sculpin	63.94	129.31	-	-	-	-	-	-	-	-	-	-	-
Tuitye (Stinky)	63.80	129.87	-	24	-	-	-	-	-	-	-	-	-
Unnamed	62.03	128.28	-	-	-	-	-	-	-	-	-	-	-
Unnamed	62.40	127.92	-	-	-	-	-	-	-	-	-	-	-
Unnamed	64.50	125.00	-	-	-	-	-	-	-	-	-	-	-

NOTES

All data from Crandall and Sadlier-Brown, 1976; and unpublished data from the Protected Areas Strategy of the NWT

[1] Fournier and Truesdell, 1973; B=1/3 for T>100°C, B=4/3 for T<100°C

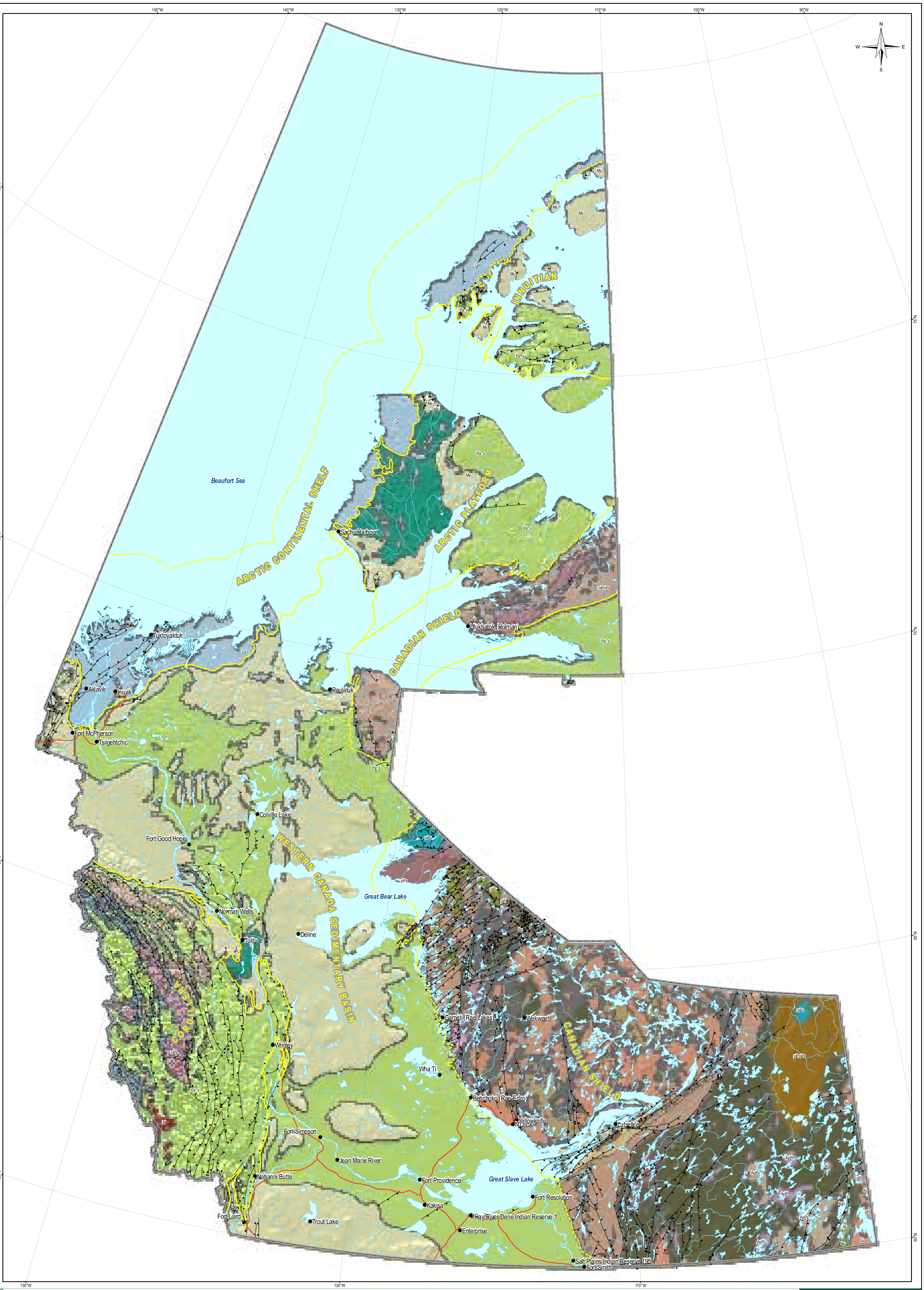
[2] Diaz-Gonzalez and Santoyo, 2008

[3] Verma and Santoyo, 1995

TABLE 4: COMMON GEOTHERMOMETER FORMULAS			
#	Formula	Source	Comment
	Alkali-based formulas		
1	T°C = {1647/ [(log(Na/K) + B(log (sqrt(Ca)/Na) + 2.06)+2.47)]} – 273.15	Fournier and Truesdell, 1973	B = 4/3 below 100°C and 1/3 above 100°C; useable for T > 70°C, best 180–300°C
2	T°C = [1217/ (log(Na/K) + 1.483)] – 273.15	Fournier 1981	Alkali formula using Na and K only
3	T°C = [876.3/ (log(Na/K) + 0.8775)] – 273.15	Diaz-Gonzalez and Santoyo, 2008	Updated using world database of geothermal fluids
4	T°C = [1289/ (log(Na/K) + 1.635)] – 273.15	Verma and Santoyo 1995	Updated using an error propagation method, with Fournier's original data
	Silica-based formulas		
5	T°C = [1309/ (5.19 – logSiO_2)] – 273.15	Fournier 1981	Silica form is quartz with no steam loss; best for T > 180°C
6	T°C = [1522/ (5.75 – logSiO_2)] – 273.15	Fournier 1981	Silica form is quartz with steam loss from reservoir; best for T > 180°C
7	T°C = [1032/ (4.69 – logSiO_2)] – 273.15	Garcher and Arehart 2008	Silica form is chalcedony; best for T = 180-140°C
8	T°C = [731/ (4.52 – logSiO_2)] – 273.15	Garcher and Arehart 2008	Form is amorphous silica; best for T < 140°C
9	T°C = -44.119 +0.24469(SiO_2) – 1.7414 E-4(SiO_2)^2 + 79.305log(SiO_2)	Verma and Santoyo 1995	Updated using an error propagation method, with Fournier's original data; useful for T = 20-210°C

Note: All concentrations in molality (mg/kg). For water with density ~1 kg/L, concentrations of mg/L can be used.

FIGURES



LEGEND

- Community
- Road
- River
- Waterbody
- NWT Border
- Fault
- Geology Region

Geology

- Archean-Proterozoic Alkaline-Mafic
- Archean-Proterozoic Granitoid
- Archean-Proterozoic Metamorphic
- Archean-Proterozoic Tectonic
- Archean-Proterozoic Unknown rocks
- Archean-Proterozoic Mixed
- Archean-Proterozoic Sedimentary
- Archean Alkaline rocks
- Archean Granitoid
- Archean Metamorphics
- Archean Intrusives
- Archean Mafic
- Archean-Paleoproterozoic Metamorphic
- Archean-Paleoproterozoic Intrusives
- Archean-Paleoproterozoic Sedimentary rocks
- Archean-Paleoproterozoic Sedimentary and Volcanics
- Archean Sedimentary
- Archean Mixed
- Archean Volcanics
- Cenozoic Sedimentary
- Mesozoic-Cenozoic Sedimentary
- Mesozoic Intrusives
- Mesozoic Sedimentary
- Proterozoic Alkaline
- Paleozoic Sedimentary
- Paleozoic Volcanic rocks
- Proterozoic Granitoid
- Proterozoic Mafic
- Proterozoic Sedimentary
- Proterozoic Volcanics
- Mesoproterozoic-Neoproterozoic Sedimentary
- Mesoproterozoic Sedimentary
- Mesoproterozoic Volcanic rocks
- Neoproterozoic-Mesozoic Sedimentary rocks
- Neoproterozoic-Paleozoic Sedimentary
- Neoproterozoic Intrusives
- Neoproterozoic Sedimentary
- Paleoproterozoic Intrusives
- Paleoproterozoic-Mesoproterozoic Intrusives
- Paleoproterozoic-Mesoproterozoic Sedimentary
- Paleoproterozoic Sedimentary
- Paleoproterozoic Volcanics

NOTES

Base data source:
Geology data from NWT Geoscience Office. Full reference:
Wheeler, J.O., Hoffman, P.F., Card, K.D., Davidson, A., Sanford, B.V., Okulitch, A.V., and Roest, W.R. (comp.) 1997: Geological Map of Canada, Geological Survey of Canada, Map D1860A.

ISSUED FOR USE

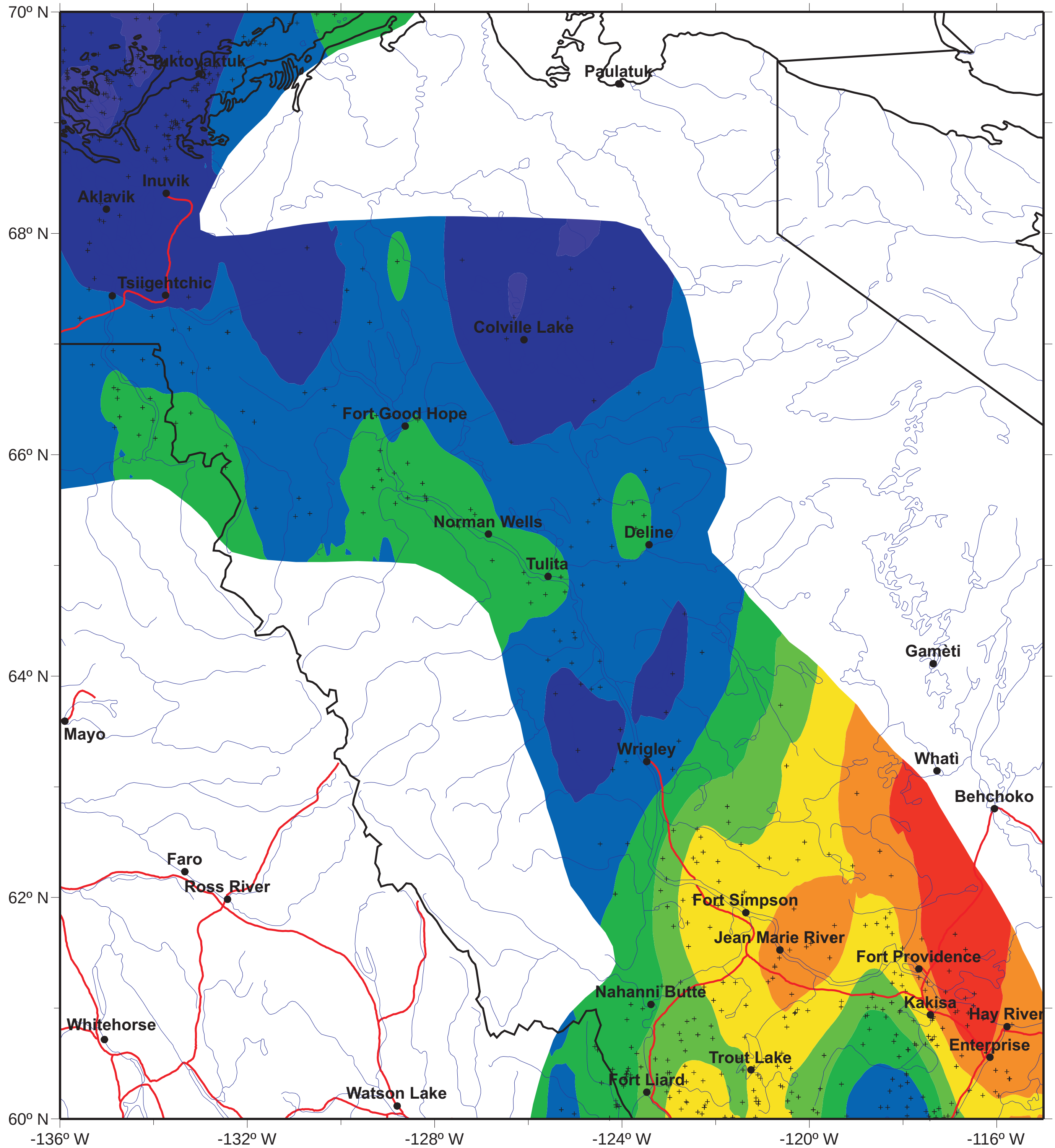
NWT GEOTHERMAL FAVOURABILITY MAPPING

Geology Map

PROJECTION: NWT Lambert	DATUM: NAD83
Scale: 1:3,000,000 (0, 25, 50, 100 Kilometers)	Northwest Territories / EBA Engineering Consultants Ltd.
FILE No: Y22101146_Figure01_Geology.mxd	DATE: April 16, 2010
JOB NO: Y22101146	REVISION NO: 1
OFFICE: EBA-VAN	DRAWN: MEZ / CHECK: SK

Figure 1

Q:\Vancouver\GIS\ENVIRONMENTAL\Y221\Y22101146_NWTGeothermalMaps\Y22101146_Figure01_Geology.mxd



ISSUED FOR USE

LEGEND

20 25 30 35 40 45 50 55 60 65 70

[ºC/km]

+ Borehole with Temperature Data

NOTES

The geothermal gradient map is based on interpolation of temperature data from 595 boreholes in NWT and Yukon. The average error of the geothermal gradient estimate is (10±5)% (Majorowicz & Morrow, 1998).

CLIENT

Northwest Territories

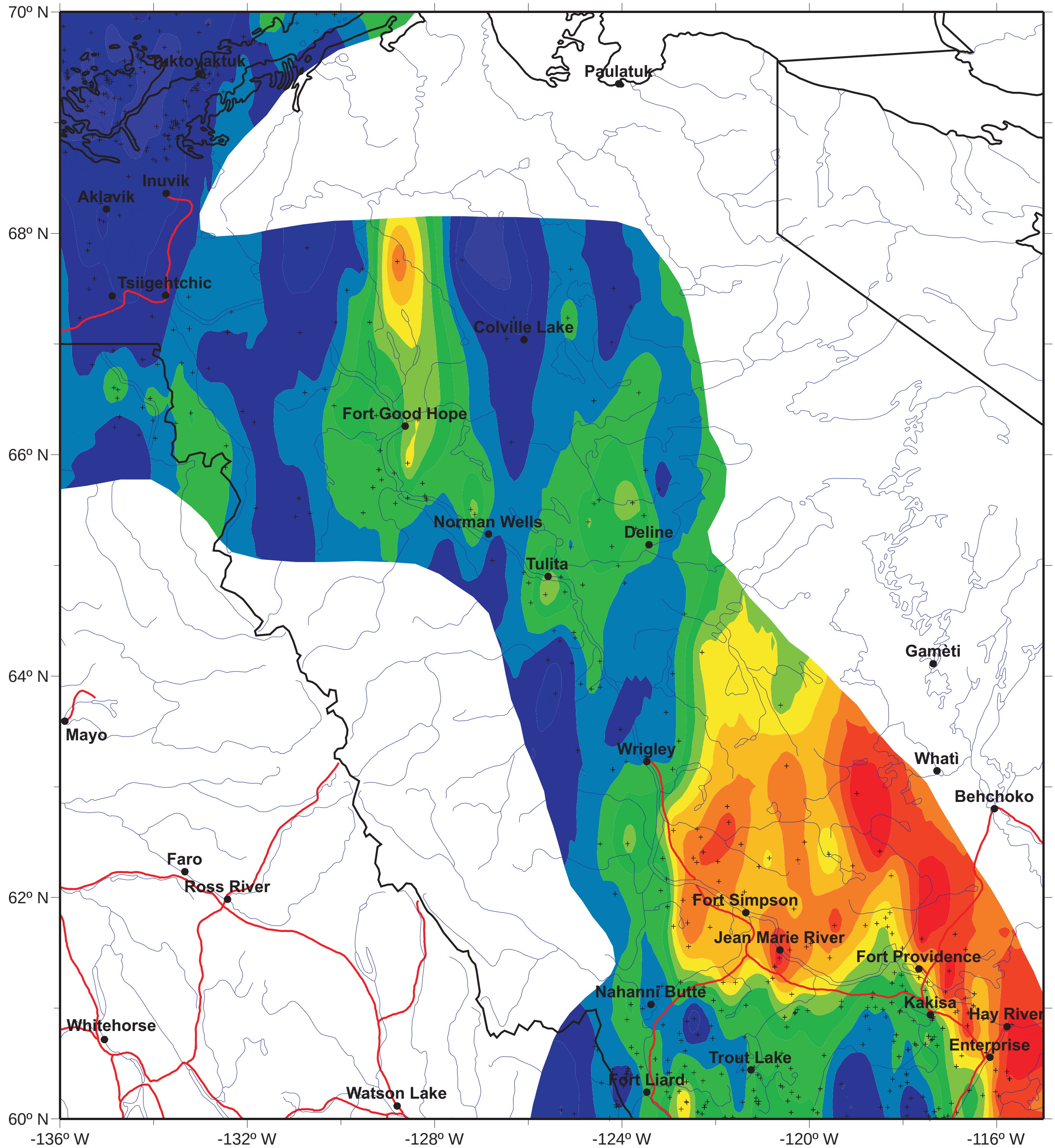
EBA Engineering Consultants Ltd.

NWT GEOTHERMAL FAVOURABILITY MAPPING

Geothermal Gradient in the Interior Platform

PROJECT NO.	DWN	CKD	REV
Y22101146	SK	JTD	0
OFFICE	DATE		
EBA-WHSE	February 2010		

Figure 2



ISSUED FOR USE

LEGEND

30 50 70 90 110 130 150

[mW/m²]

\+ Borehole with Temperature Data

NOTES

The heat flow map is based on interpolation of heat flow data from 595 boreholes in NWT and Yukon (Majorowicz & Morrow, 1998).

CLIENT

Northwest Territories

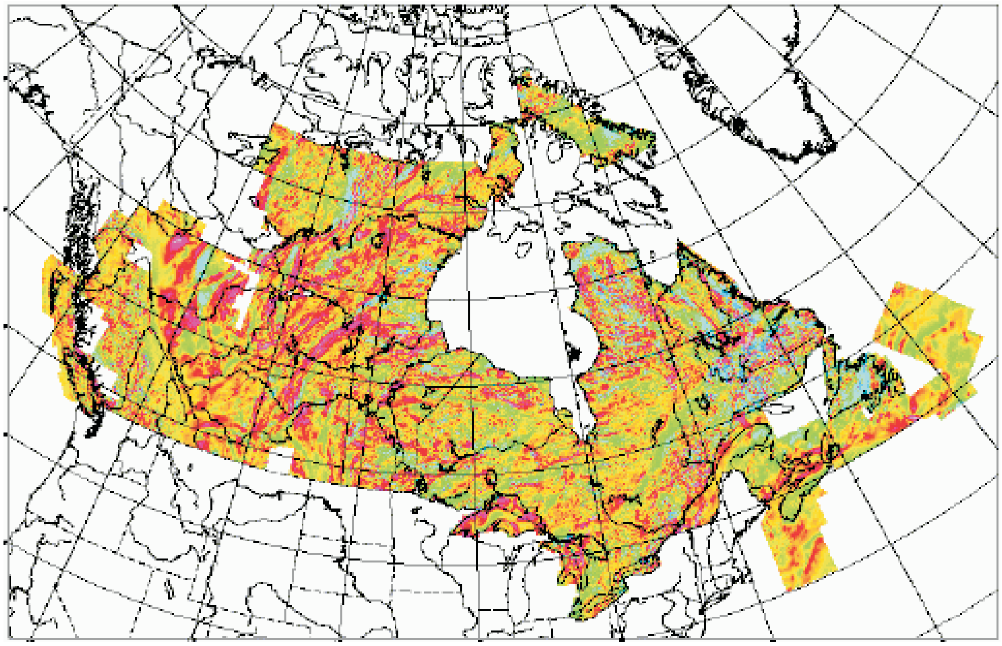
EBA Engineering Consultants Ltd.

NWT GEOTHERMAL FAVOURABILITY MAPPING

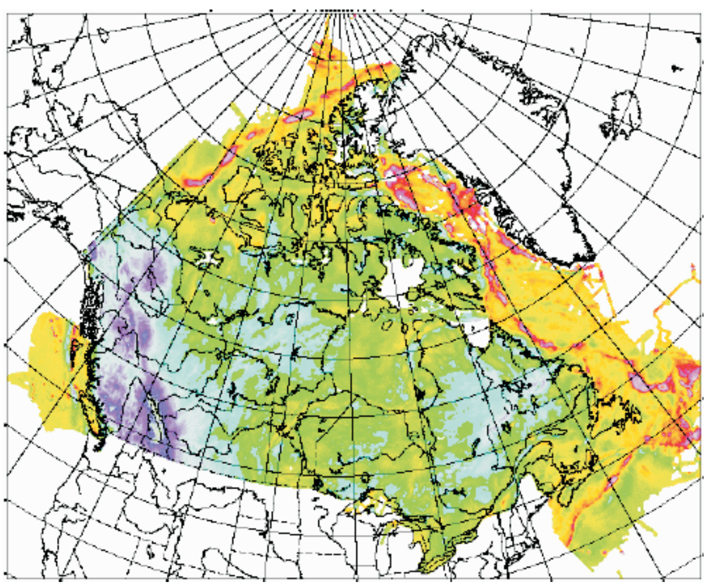
Heat Flow in the Interior Platform

PROJECT NO.	DWN	CKD	REV
Y22101146	SK	JTD	0
OFFICE	DATE		
EBA-WHSE	February 2010		

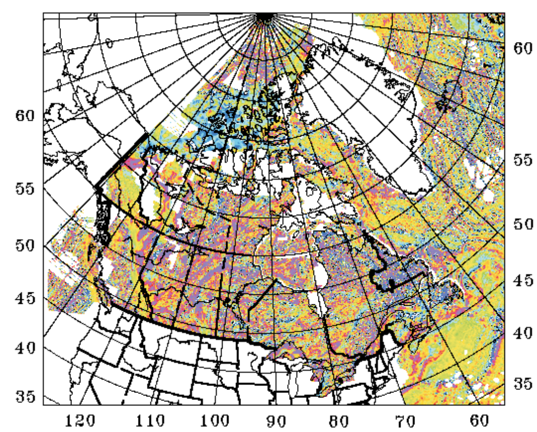
Figure 3



Levelled magnetic data coverage



Gravity data coverage



Total magnetic data coverage

CLIENT

Northwest Territories

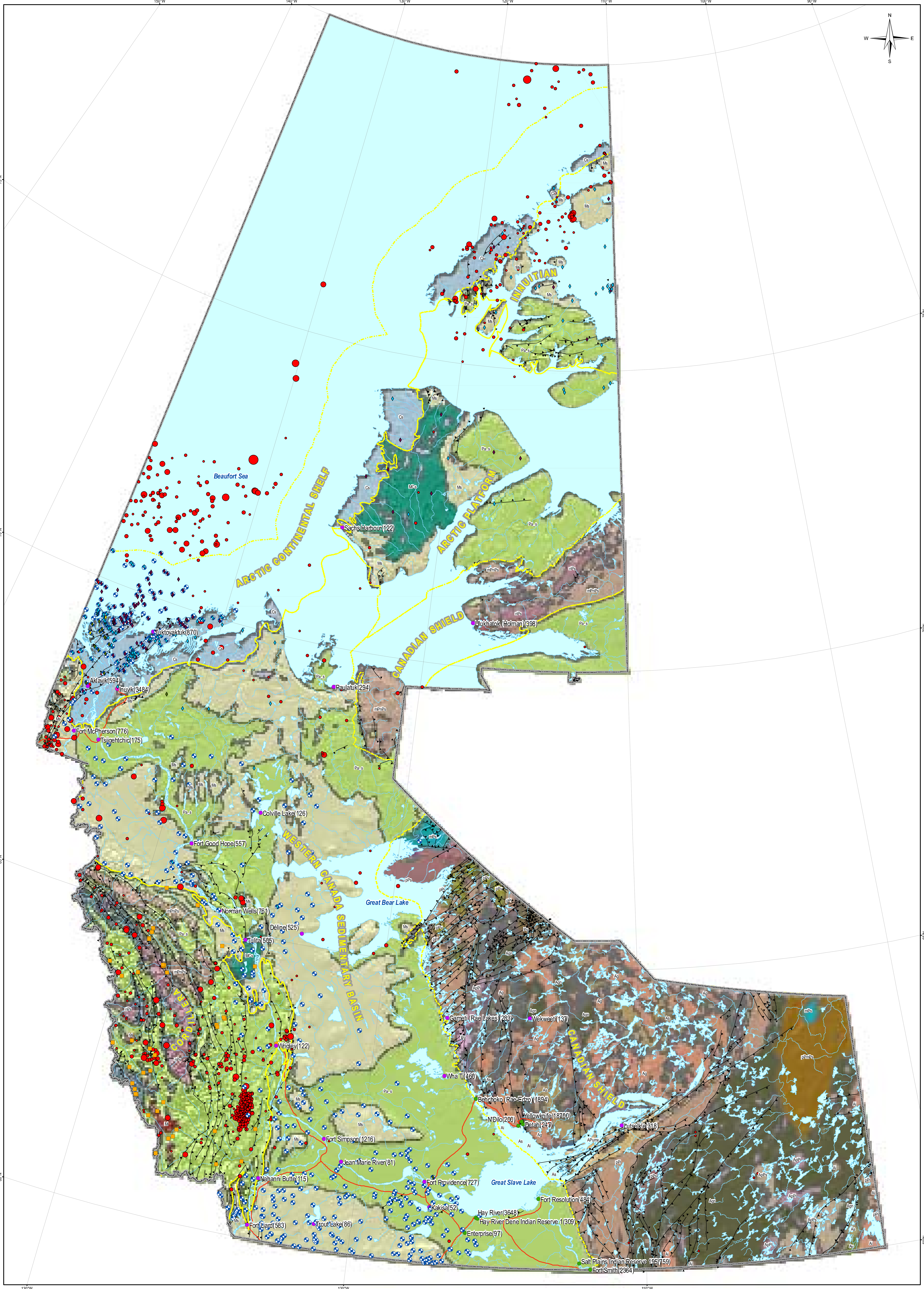
NWT GEOTHERMAL FAVOURABILITY MAPPING

Gravity and magnetic data coverage of Canada, available from NRC

EBA Engineering Consultants Ltd.

eba

Y22101146	DWN JWL	CKD SK	REV	Figure 4
OFFICE EBA-RIV	DATE March 2010			



LEGEND

Community (Population)

Energy Supply
- Diesel
- Hydro
- Natural Gas
- Road
- River
- Waterbody
- NWT Border

- Known Hot or Warm Spring
- Well Location

Base of Ice Bearing Permafrost (m)
- No Permafrost
- <10
- 10-50
- 50-100
- 100-500
- >500

Earthquake Location Magnitude
- 2.5-3
- 3-3.5
- 3.5-4
- 4-4.5
- 4.5-5
- 5-5.5
- 5.5-6
- 6-6.5
- 6.5-7

- Fault
- Geology Region

Geology
- Archean-Proterozoic Alkaline-Mafic
- Archean-Proterozoic Granitoid
- Archean-Proterozoic Metamorphic
- Archean-Proterozoic Tectonic
- Archean-Proterozoic Unknown rocks
- Archean-Proterozoic Mixed
- Archean-Proterozoic Sedimentary
- Archean Alkaline rocks
- Archean Granitoid
- Archean Metamorphics
- Archean Intrusives
- Archean Mafic
- Archean-Paleoproterozoic Metamorphic
- Archean-Paleoproterozoic Intrusives
- Archean-Paleoproterozoic Sedimentary rocks
- Archean-Paleoproterozoic Sedimentary and Volcanics
- Archean Sedimentary
- Archean Mixed
- Archean Volcanics
- Cenozoic Sedimentary
- Mesozoic-Cenozoic Sedimentary
- Mesozoic Intrusives
- Mesozoic Sedimentary
- Proterozoic Alkaline
- Paleozoic Sedimentary
- Paleozoic Volcanic rocks
- Proterozoic Granitoid
- Proterozoic Mafic
- Proterozoic Sedimentary
- Proterozoic Volcanics
- Mesoproterozoic-Neoproterozoic Sedimentary
- Mesoproterozoic Sedimentary
- Mesoproterozoic Volcanic rocks
- Neoproterozoic-Mesozoic Sedimentary rocks
- Neoproterozoic-Paleozoic Sedimentary
- Neoproterozoic Intrusives
- Neoproterozoic Sedimentary
- Paleoproterozoic Intrusives
- Paleoproterozoic-Mesoproterozoic Intrusives
- Paleoproterozoic-Mesoproterozoic Sedimentary
- Paleoproterozoic Sedimentary
- Paleoproterozoic Volcanics

ISSUED FOR USE

NOTES

Base data sources:

Geology data from NWT Geoscience Office. Full reference:
Wheeler, J.O., Hoffman, P.F., Card, K.D., Davidson, A., Sanford, B.V., Okulitch, A.V., and Roest, W.R. (comp.) 1997: Geological Map of Canada, Geological Survey of Canada, Map D1860A.

Permafrost Data from Smith, S.L. and Burgess, M.M. (2002) A Digital Database of Permafrost Thickness in Canada, Geological Survey of Canada Open File Report No. 4173

Earthquake Data from Halchuck, S. (2009) Seismic Hazard Earthquake Epicentre File (SHEEF) used in the fourth generation seismic hazard maps of Canada, Geological Survey of Canada Open File Report No. 6208

Hot Springs Data from Crandall, J.T. and Sadlier-Brown, T.L. (1976) Data on geothermal areas Cordilleran Yukon, Northwest Territories, and adjacent British Columbia, Canada. Energy, Mines and Resources Canada, Earth Physics Branch, Open File Report No. 78-1, 23 p.
and
Unpublished data from the Protected Areas Strategy of the NWT (pers. comm.)

Well data from Majorowicz, J. A. and Morrow, D. W., 1998, Subsurface Temperature and Heat Flow – Yukon and Northwest Territories, Geological Survey of Canada Open File 3626

NWT GEOTHERMAL FAVOURABILITY MAPPING

GIS Data Compilation

PROJECTION: NWT Lambert	DATUM: NAD83
Scale: 1:3,000,000 (0 25 50 100 Kilometers)	
FILE No: Y22101146_Figure05_DataCompilation.mxd	DATE: April 16, 2010
JOB NO: Y22101146	REVISION NO: 1
OFFICE: EBA-VAN	DRAWN: MEZ / CHECK: SK

Northwest Territories

EBA Engineering Consultants Ltd.

Figure 5

Q:\Vancouver\GIS\ENVIRONMENTAL\Y221\Y22101146_NWTGeothermal\Maps\Y22101146_Figure05_DataCompilation.mxd

NWT GEOTHERMAL FAVOURABILITY MAPPING

Geothermal Favourability Map

PROJECTION: NWT Lambert	DATUM: NAD83	Northwest Territories EBA Engineering Consultants Ltd. eba
Scale: 1:3,000,000 0 25 50 100 Kilometers		
FILE No: Y22101146_Figure06_GeoFav.mxd		DATE: April 14, 2010
JOB NO: Y22101146	REVISION NO: 1	**Figure 6**
OFFICE: EBA-VAN	DRAWN: MEZ	CHECK: SK

ISSUED FOR USE

APPENDIX A

APPENDIX A EBA'S GENERAL CONDITIONS

GEO-ENVIRONMENTAL REPORT – GENERAL CONDITIONS

This report incorporates and is subject to these “General Conditions”.

1.0 USE OF REPORT AND OWNERSHIP

This report pertains to a specific site, a specific development, and a specific scope of work. It is not applicable to any other sites, nor should it be relied upon for types of development other than those to which it refers. Any variation from the site or proposed development would necessitate a supplementary investigation and assessment.

This report and the assessments and recommendations contained in it are intended for the sole use of EBA’s client. EBA does not accept any responsibility for the accuracy of any of the data, the analysis or the recommendations contained or referenced in the report when the report is used or relied upon by any party other than EBA’s Client unless otherwise authorized in writing by EBA. Any unauthorized use of the report is at the sole risk of the user.

This report is subject to copyright and shall not be reproduced either wholly or in part without the prior, written permission of EBA. Additional copies of the report, if required, may be obtained upon request.

2.0 ALTERNATE REPORT FORMAT

Where EBA submits both electronic file and hard copy versions of reports, drawings and other project-related documents and deliverables (collectively termed EBA’s instruments of professional service), only the signed and/or sealed versions shall be considered final and legally binding. The original signed and/or sealed version archived by EBA shall be deemed to be the original for the Project.

Both electronic file and hard copy versions of EBA’s instruments of professional service shall not, under any circumstances, no matter who owns or uses them, be altered by any party except EBA. The Client warrants that EBA’s instruments of professional service will be used only and exactly as submitted by EBA.

Electronic files submitted by EBA have been prepared and submitted using specific software and hardware systems. EBA makes no representation about the compatibility of these files with the Client’s current or future software and hardware systems.

3.0 NOTIFICATION OF AUTHORITIES

In certain instances, the discovery of hazardous substances or conditions and materials may require that regulatory agencies and other persons be informed and the client agrees that notification to such bodies or persons as required may be done by EBA in its reasonably exercised discretion.