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CanGEA
CANADIAN GEOTHERMAL ENERGY ASSOCIATION

Geothermal Resource Estimate Maps of Yukon following a Global Protocol – Methods and Data Sources

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Background

Geothermal energy, despite its potential to provide low cost, clean, green, continuous base load power, has remained underdeveloped compared to other renewable energies. High capital costs in the pre-development phase, along with a lack of knowledge in the various geothermal technologies has held back investment opportunities for this energy resource. While recent reports from the Federal Government[1] have been key in indicating the geothermal resource potential of Canada, further steps need to be taken to provide technical data pertinent to geothermal exploration. The need to standardize geothermal resource evaluation and reporting methods has been addressed by several international bodies in the geothermal industry.

Following Proceedings of the Geothermal Resources Council Annual Meeting in 2010[2], a framework for a Global Protocol to estimate and map the Theoretical Potential and Technical Potential[3] for Enhanced Geothermal Systems was published. This Global Protocol has since been reviewed and endorsed by the International Geothermal Association (IGA), the Executive Committee of the International Energy Agency Geothermal Implementing Agreement (IEA-GIA), and the International Heat Flow Commission (IHFC).

The Global Protocol currently provides a globally consistent manner for estimating and mapping geothermal potential suitable for development using Enhanced Geothermal Systems. Australia (2010) and the US (2011), in cooperation with Google.org, recently completed maps following the Global Protocol. The U.S. maps are publicly available for interactive display on the Google website (www.google.org/egs). South Korea and Europe recently completed Global Protocol maps as well in 2010 and 2013 respectively.

In 2011 CanGEA set out to map high priority areas of the country using an internationally accepted methodology. The Global Protocol was chosen and adapted as necessary to include all geothermal resources, not limited to EGS only. The maps completed in 2013 for the province of Alberta and the Canadian National Geothermal Database (CNGD) can be publicly accessed by visiting the following website: http://www.cangea.ca/canadian-national-geothermal-database-and-resource-favourability-maps.html. They are also joined by the British Columbia maps completed in 2014 and the Yukon maps completed in 2015.

[1] Grasby et al., 2011
[2] Beardsmore et al., 2010
[3] as defined by Rybach, 2010

In addition, efforts to standardize the reporting of geothermal resources and reserves have been undertaken by the Australian Geothermal Energy Association (AGEA) and CanGEA through the development of Geothermal Codes for Public Reporting.

1.0 Introduction

Following the guidelines set forth by the Global Protocol and the Canadian Geothermal Code for Public Reporting, CanGEA has facilitated the development of the Geothermal Resource Estimate Maps of the Yukon with the goal of demonstrating Yukon's geothermal resource potential within a global context. Presented to the public in a universal mapping platform format and centralized national geothermal database, the project deliverables provide a means to share, collaborate and update the data necessary for making informed commercial decisions around geothermal development. The Geothermal Resource Estimate Maps of the Yukon and associated database are tools for advancing geothermal development within the Yukon.

A partial Canadian National Geothermal Database (CNGD) had already been developed with the completion of the Alberta Geothermal Favourability Maps[4] in 2013 and of BC in 2014. This database has now been expanded with the inclusion of data for the Yukon. The Methods and Data Sources report represents the Canadian adaption of the Global Protocol for Estimating and Mapping Geothermal Potential and has undergone a detailed review by 'Qualified' (as defined by the Code) individuals from Australia's Protocol development team, along with authors of the Canadian Geothermal Code for Public Reporting (Toohey *et al.,* 2010) (http://www.cangea.ca/geothermal-code-for-public-reporting.html). Anticipating any future changes and/or advancements in geothermal technology, the Canadian application of the Global Protocol will serve as a 'living document' and will remain open to continuous review.

The opportunity to establish a geothermal industry in the Yukon offers numerous benefits and advantages. As production of geothermal energy continues to grow around the world, so will the need to estimate and map geothermal resources in a globally consistent manner. By adopting these practices in the pre-development phase, the Yukon sets itself up to a high-level industry standard that is compatible with current and future development. Additionally, geothermal developments will not only increase the international movement of skilled personnel to the Yukon, but will also provide opportunities for technology transfer from the already present population of personnel skilled in well drilling, reservoir management and resource exploration. International collaboration and in-kind support from multiple parties involved in this project has already led to new ideas in geothermal resource assessment and data quality control.

[4] CanGEA, 2013

As the maps and geothermal database produced by this project are shared publicly via a web portal and Google Earth platform, virtually anyone now has the opportunity to learn about the geothermal potential in the Yukon. Data gaps will also be identified, encouraging multiple industries to contribute, update and share new and existing data to the national database. These maps will help to identify regions of the Yukon with clearly defined data gaps where further research is recommended. By promoting collaboration, it is anticipated that the project will lead to other geothermal mapping and resource estimate projects for the remainder of Canada.

2.0 Project Deliverables

Deliverable	Description
1	Where possible, all the relevant data to substantiate the production of the Yukon Maps. This data has been collected as publicly available layers and datasets and has been presented through a GIS system.
2	A database summarizing all of the acquired and calculated data that can be publicly disclosed.
3	A full set of references for all data acquired and used in this exercise (Appendix I).
4	A set of digital maps presenting the data in a manner consistent with the formats and legends used in the BC Geothermal Favourability Map. The list of maps produced is summarized in Appendix II.
5	All work performed is in general accordance with the Global Protocol for Geothermal Reporting and the Canadian Geothermal Code for Public Reporting. In areas where these do not apply, the work conforms to "Exploration Best Practices" as defined in the Canadian Institute of Mining National Instrument 43-101.

3.0 Canadian National Geothermal Database and Map Portal

The Canadian National Geothermal Database (CNGD) and Map Portal stores critical geothermal site attribute information. It is similar in scope and intent to the U.S. National Geothermal Data System ('NGDS'; www.geothermaldata.org). The CNGD strives to store such data as:

- temperature at depth, thermal conductivity, heat flow, well logs, bottom hole temperatures (BHT), drill stem test (DST), permafrost data, seismicity/microseismicity, porosity/permeability data, water chemistry, geophysical surveys, etc.

It is relevant to all types of geothermal energy potential, such as:

- direct-use, hydrothermal, hot sedimentary aquifer, geo-pressured, Enhanced Geothermal Systems (EGS), geothermal fluids co-produced with oil and/or gas and minerals (mining), etc.

The Yukon Resource Estimate Maps and Database stores the following data:

- temperature at depth, thermal conductivity, heat flow, well logs, bottom hole temperatures (BHT) and drill stem test (DST) data

Data stored in the Database includes historical data and geothermal resource assessment data compiled by universities, research organizations, and private and publicly funded geothermal exploration projects. In addition to regions with geographically proximal data, the Database will also allow interpolation or extrapolation of trends to assess regions of Canada that lack the required local data for assessing geothermal potential. The Database will be made available to the public and will serve as a geothermal exploration tool for making informed business decisions, and as a means for mitigating investment risks. The Database was established and is hosted by CanGEA.

3.1 Data Organization, Formatting, and Verification

A web portal will provide public access to the CNGD. Data is organized based on specific criteria such as location and temperature (i.e. low temperature for direct use, moderate/high temperature for electricity generation, etc.). The web portal is user-friendly and flexible, allowing data to also be retrieved for specific geological, geophysical, environmental and/or other purposes related to assessing and identifying geothermal potential.

Data is stored in standard data measurement units (SI units) and documented to ensure quality and validation. Verification and QA/QC of the data is completed throughout the various phases of the mapping project.

3.2 Data Sources and Description

The data underpinning the Geothermal Resource Estimate Maps of Yukon was obtained from both private and public sources. Data types varied between raw data in text and excel file format to shape files for import into Geographic Information Systems. Descriptions of all data sets are provided below, and sources are given in Appendix I.

3.3 Base map data

The base map data is made up of several topographic themes containing natural resource and land management information. These layers form the core of the Resource Estimate Maps and are the base from which all of the maps are created.

3.3.1 Grid Systems

NTS (National Topographic System) Grid

Mapping for this project was done using the NTS (National Topographic System) grid. This grid is a departure from the size recommended by the Global Protocol. It was chosen because it is a nation-wide standard that is recognized and used across many different industries in Canada, and will be used to map all of the provinces and territories of the country.

The NTS grid is a standard geographic numbering system that identifies topographic map coverage for all of Canada. The nation is divided into primary quadrangles of 4° of latitude and 8° of longitude. Each of these quadrangles is further broken down into 16 letter blocks (A-P) of 1° of latitude and 2° of longitude. The 1:50,000 (50K) grid divides these letter blocks into 16 more cells (numbered 1-16), of size 15' latitude by 30' longitude. Each individual grid cell varies in size with an average area of 7.2 x 10^8 m^2 (24 x 27km). This grid system abruptly changes above the 68^{th} parallel where the NTS grids are doubled in area and merged across lines of longitude as they converge towards the pole. Some of the well data drilled along the northern coast intersects two of these NTS grid cells and were preserved to maintain consistency with the NTS grid system used throughout the rest of the territory. Using this grid system, the territory of the Yukon was divided up into 731 individual grid cells, which provided the surface grid framework for estimating the geothermal potential of the Yukon.

Using the grid system, the local thermal structure is estimated for each of the grid cells using a 1D heat conduction model, and then the total potential in the region is estimated by summing together the discrete estimates of each cell.

This grid system was obtained from the Yukon Geological Survey's- Geo-Data Downloads website.

5'x5' Grid

The Yukon was also mapped using an alternate grid system: a 5'x5' regularly spaced grid. The Global Protocol recommends that the region be divided into a regular grid composed of 5'x5' graticules, which are evenly-spaced lines of latitude and longitude that define the size of the grid cells. This grid system, which was created in-house, divided the territory up into 12,769 individual grid cells. The additional mapping for the 5'x5' grid was done as an exercise to determine what effect, if any, the change in grid cell size would have on the resource estimate results.

Given the small number of wells with bottom hole temperature data (64) the NTS system showed a mapped data coverage of 4.9% of the territory, while the 5'x5' system showed just 0.4%. The resource estimates for each showed a similar trend, with those numbers being summarized in the tables below.

Technical Potential for Geothermal in Yukon
NTS Grid Version
Values Indicate Potential Power (Indicated and Inferred Resources)

Recovery	Depth	Generation Potential	
		Indicated Resources	Inferred Resources
5%	1,500m:	92 MW	0 MW
	2,500m:	542 MW	716 MW
	3,500m:	724 MW	1,665 MW
	4,500m:	424 MW	2,544 MW
	Total:	1,782 MW	4,926 MW
14%	1,500m:	258 MW	0 MW
	2,500m:	1,517 MW	2,006 MW
	3,500m:	2,027 MW	4,663 MW
	4,500m:	1,186 MW	7,124 MW
	Total:	4,989 MW	13,793 MW
20%	1,500m:	369 MW	0 MW
	2,500m:	2,167 MW	2,865 MW
	3,500m:	2,896 MW	6,661 MW
	4,500m:	1,695 MW	10,177 MW
	Total:	7,127 MW	19,704 MW
		Installed Generation Capacity (All Sources):	**0 MW**

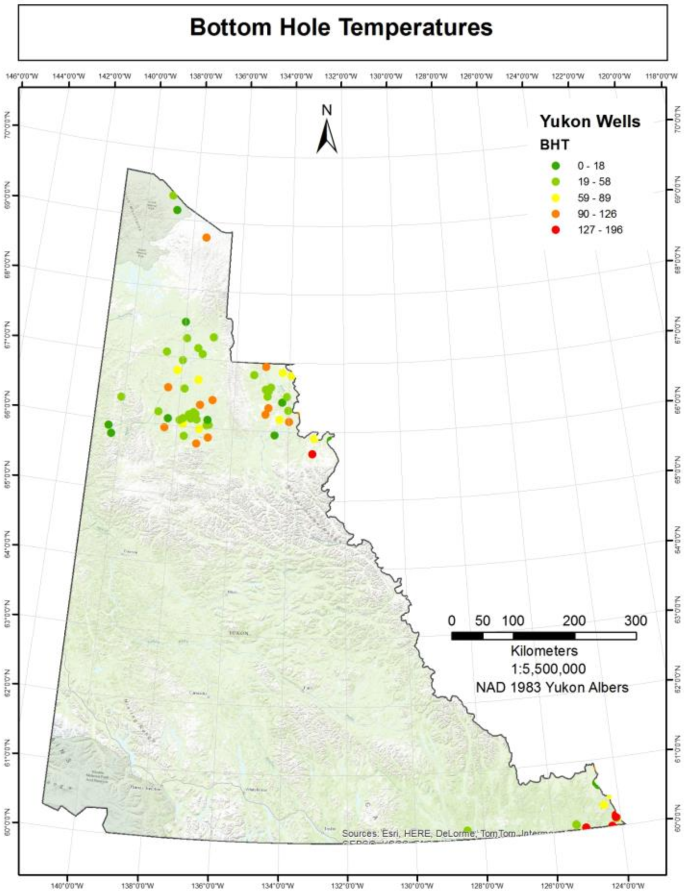
Technical Potential for Geothermal in Yukon
5x5 Grid Version
Values Indicate Potential Power (Indicated and Inferred Resources)

Recovery	Depth	Generation Potential	
		Indicated Resources	Inferred Resources
5%	1,500m:	5 MW	0 MW
	2,500m:	16 MW	56 MW
	3,500m:	40 MW	127 MW
	4,500m:	31 MW	192 MW
	Total:	92 MW	375 MW
14%	1,500m:	14 MW	0 MW
	2,500m:	45 MW	155 MW
	3,500m:	113 MW	357 MW
	4,500m:	86 MW	537 MW
	Total:	258 MW	1,049 MW
20%	1,500m:	20 MW	0 MW
	2,500m:	64 MW	222 MW
	3,500m:	161 MW	509 MW
	4,500m:	122 MW	768 MW
	Total:	368 MW	1,499 MW
		Installed Generation Capacity	**0 MW**

Mapped coverage using NTS: 4.9%

Mapped coverage using 5'x5': 0.4%

As an example of what the subsurface temperature data coverage in the Yukon looks like, the figure below is a map showing all of the bottom hole temperature data points that were collected.



3.3.2 National Parks, Territorial Parks, and assorted Protected Areas

This data was collected from the NRCan website and included national and territorial park boundaries, wildlife areas and sanctuaries, ecological reserves, wilderness preserves and special management areas. More specific information related to each administrative boundary can be found in the Entity and Attribute section.

3.3.3 Territorial Boundary

Compiled by NRCan, the Yukon Boundary polygon layer contains the polygon that represents the location of the boundaries of the Yukon.

3.3.4 Aboriginal Lands

The Aboriginal Lands product consists of polygon entities that depict the administrative boundaries (extent) of lands where the title has been vested in specific Aboriginal Groups of Canada or lands that were set aside for their exclusive benefit. Please note that this data set is not to be used for defining boundaries. Administrative decisions should be based on legal documents and legal survey plans. More information on the individual Indian Reserves, Settlement Lands and Indian Lands contained in the Aboriginal Lands Dataset can be found at the following web site: http://www.clss.nrcan.gc.ca and ftp://ftp.geomaticsyukon.ca/GeoYukon/First_Nations/

3.4 Transmission Grid

The transmission line map for the Yukon was obtained from Government of Yukon through their website (ftp://ftp.geomaticsyukon.ca/GeoYukon/Utilities_and_Communication/), with updates from Yukon Energy. The transmission lines represent the bulk and regional transmission lines that provide power to the territory through lines of varying capacity.

3.5 Bottom Hole Temperature and Heat Flow Data

The subsurface temperature data is comprised of measurements from oil and gas wells that were obtained from the Government of Yukon website (ftp://ftp.geomaticsyukon.ca/GeoYukon/Oil_and_Gas/) and from third party sources including Accumap

Borehole data was also obtained from boreholes catalogued in the Canadian Geothermal Data Compilation[5]. The compilation contains the measured data of the Geothermal Group of the Earth Physics Branch from 1962 to 1986, data acquired by the Geological Survey from 1986 to present, and data from universities and contractors. The data was collected from wells and boreholes at 1,958 sites throughout Canada and include temperature, thermal conductivity, heat generation, petrological descriptions, and information on which to base corrections for inclination of the well and glacial history.

Heat flow data was obtained from borehole data from the North American Borehole (NABH) dataset from the University of Michigan's Global Database hosted on NOAA's National Climatic Data Centre[6]

3.6 Surface Temperature

Surface temperature measurements used for the Yukon were a compilation of data obtained from Environment Canada.

[5] Jessop et al., 2005
[6] Jessop & Wang, 2008

The 'Second Generation of Homogenized Temperature' datasets from Environment Canada were prepared to provide a spatial and temporal representation of the climate trends in Canada. Non-climatic shifts were identified in the annual means of the daily maximum and minimum temperatures using a technique based on regression models. Datasets were provided for 338 locations across the country. Observations from nearby stations were sometimes combined to create long time series. Data series were extended to cover the period 1895-2008 as much as possible.

3.7 Sediment Thickness

Data for sediment thickness in the Yukon is quite sparse and as a result, the thickness of the sediment package that overlies either pre-Cambrian basement rock, or metamorphic/igneous crystalline rock - heretofore referred to as "depth to basement" - was estimated by calculating isopachs for major time divisions represented in the bedrock geology coverage, thickness values of which were compiled from two datasets:

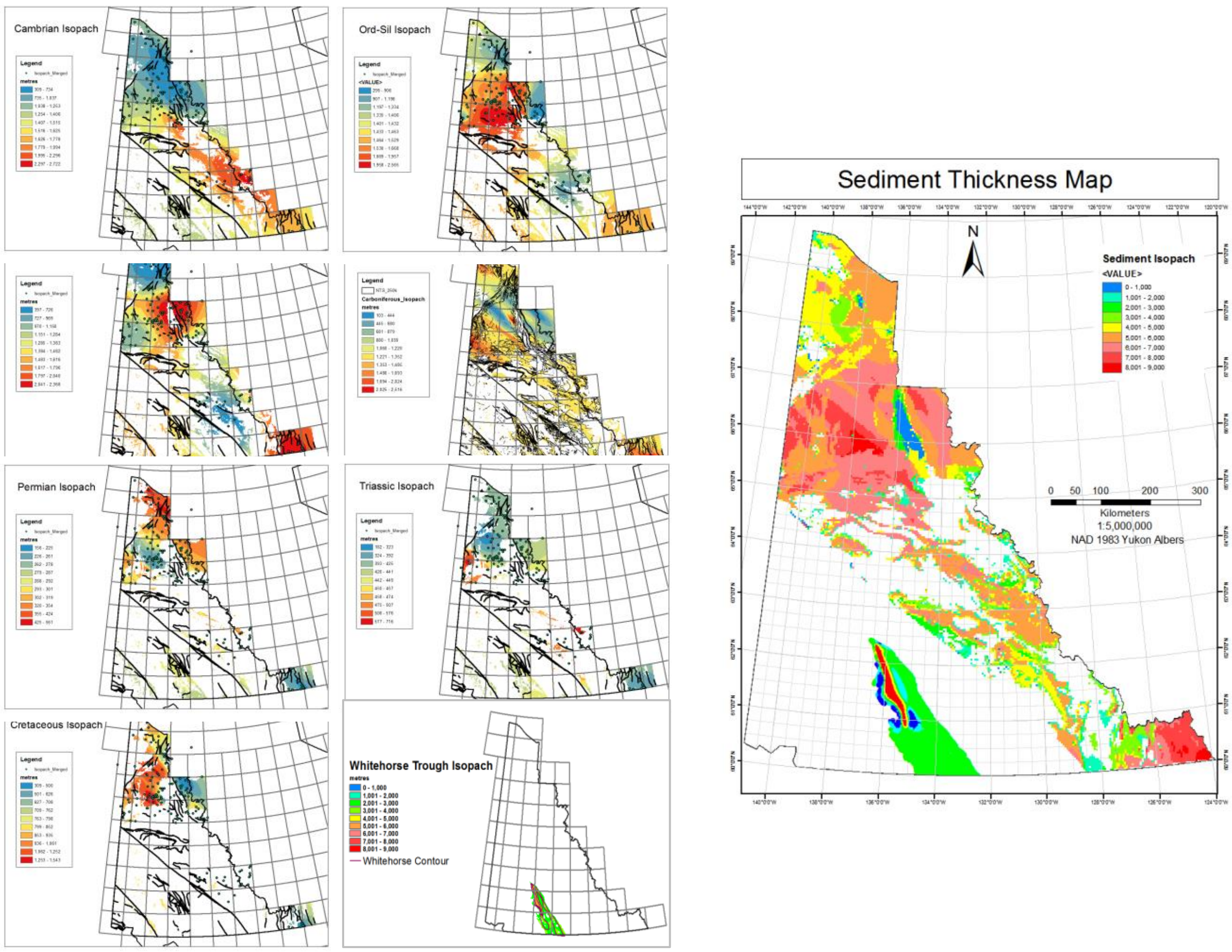
- Sediment thickness of each major time division gathered from reclassified formation top intersections in oil and gas well data set.
- Sediment thickness estimates of sediment outcrop from literature compiled and reclassified to reflect approximate major time divisions (Abbot, Gordey, Gordey et al, and Norris).

Isopachs for each major time division were gridded using global krigging estimates and then masked out using polygons derived from exposed sediments that were older than the time division in question. These masked regions were essentially an efficient proxy to a mapped erosional boundary of the isopach being calculated.

The Whitehorse Trough sediment thickness was estimated using a broad contoured interpretation from literature (White et al) to estimate the large scale thickness changes across the basin where sediments were inerpreted to be thicker towards the north western side of the trough.

All thickness estimates are meant to be broad interpretations only in order to facilitate the heat calculations. Further refinement of basin sediment thickness is recommended, although any thicknesses that are greater than 5,000m will not affect the results as no heat model calculations were done below this depth.

The figure below shows a series of images illustrating how the above datasets were used in combination to estimate the thickness of the sedimentary cover across the territory.



3.8 Thermal Properties

Default values of thermal conductivity, heat production rate, density and heat capacity of sediments and basement rocks were applied as recommended by the Global Protocol.

4.0 Yukon Resource Estimate Maps

All maps were created using Geographic Information Systems software (ArcMap 10.3) and projected to the North American Datum 1983 (NAD83) Yukon Albers UTM coordinate system. All shallow systems, deep systems, heat flow, conductivity, geothermal gradients, depth to basement, surface temperature, along with the Theoretical and Technical potential were calculated at the 5' x 5' grid scale and up-scaled using area weighting to the NTS grid scale. Regions with no known data points were not included in the analysis and those grid cells containing no data were left blank (i.e. they appear as transparent). This helped to identify regions of the Yukon with clearly defined data gaps where further research is recommended.

4.1 Assumptions

All calculations closely followed the Global Protocol published in the Proceedings of the Geothermal Resources Council Annual Meeting 2010[7].

The Global Protocol states that a fundamental assumption in this process is that pure vertical conduction is the dominant mechanism of heat transfer through the crust, and thus calculations done assume a 1D heat conduction model. However, besides the northeastern half of the territory that is divided by the Tintina Fault system, the geology throughout the south western half of the Yukon is complex and metamorphic, igneous, or volcanic in nature where it could not be proven that conduction is the dominant heat transfer mechanism, based on available data. After discussing the issue with the international community, it was determined that though other areas with similar geology (e.g., the Cascades region in the United States) are experiencing a similar challenge, there does not currently exist any modifications to the Protocol that account for geologic regions such as those likely to be found in the Yukon where heat transport might occur by other means, such as fluids moving along fractures and fault zones. In the absence of an alternative, the original assumptions from the protocol were used and implemented for the calculations performed.

As stated earlier, the Yukon is split into two main areas by the northwest trending Tintina fault zone. North and east of this prominent physiographic feature, sediments of various depositional periods (pre-Cambrian to Cretaceous and Paleogene) are preserved and represent accumulation of sediment along the ancient, north-western edge of the North American Continent and ancient inland sea. The southeastern tip of the Yukon similarly represents the tip of a thick wedge of the northwestern portion of the Western Canada Sedimentary Basin (WCSB). Any rock formations deposited or formed earlier than Cambrian time, was assumed to be crystalline in nature and classified as "basement" rock. South and west of the Tintina fault, most of the rocks are volcanic, metamorphic, or plutonic in origin, with the exception of the Whitehorse Trough - a wedge of sediment representing a period of deposition that occurred in the Mesozoic in an inland sea depositional environment – similar to the Bowser basin in BC.

[7] Beardsmore et al., 2010

Most of the underlying Lower Proterozoic sedimentary and metamorphic/volcanic/igneous rock complexes have lost permeability by being metamorphosed to a high grade state and are therefore also considered "basement" rock for the purposes of geothermal conductivity. For both Alberta and BC to the south, a large portion of the WCSB was key to the production of the resource maps generated for these provinces, where heat was assumed to be under transport only by conduction. The same assumptions also went into the production of the Yukon maps for rock that was clearly sedimentary in origin and relatively undisturbed (i.e. not significantly altered), and where the heat flow in the sedimentary column is assumed to be vertical and uniform:

- if there are no significant proximal lateral variations in the thermal conductivity of the rocks (as is assumed to be the case within the Western Canada Sedimentary Basin),
- if the rate and volume of groundwater flow is negligible (an assumption still the object of debate), and
- if heat generation with the sediment is negligible (see below).

Given these assumptions, the vertical temperature profile and variation of the geothermal gradient are determined by the heat flow at the base of the sedimentary column and by the thermal conductivity of the rocks.)

4.2 Methods

4.2.1 Quality Assurance/Quality Control

For the Yukon Resource Estimate Maps, the initial set of temperature at depth data was provided absent any Quality Assurance/Quality Control (QA/QC) review.

Reviewing each data point individually was doable, given the small number of valid bottom hole temperatures recorded. A 'filtering' process was used to exclude anomalous data points and remain consistent.

The process is as described below:

1. The data was grouped into depth 'bins' corresponding to the various depths at which maps are produced.

2. Within each bin, an aggregate predictive trend was identified, based on the totality of the data.

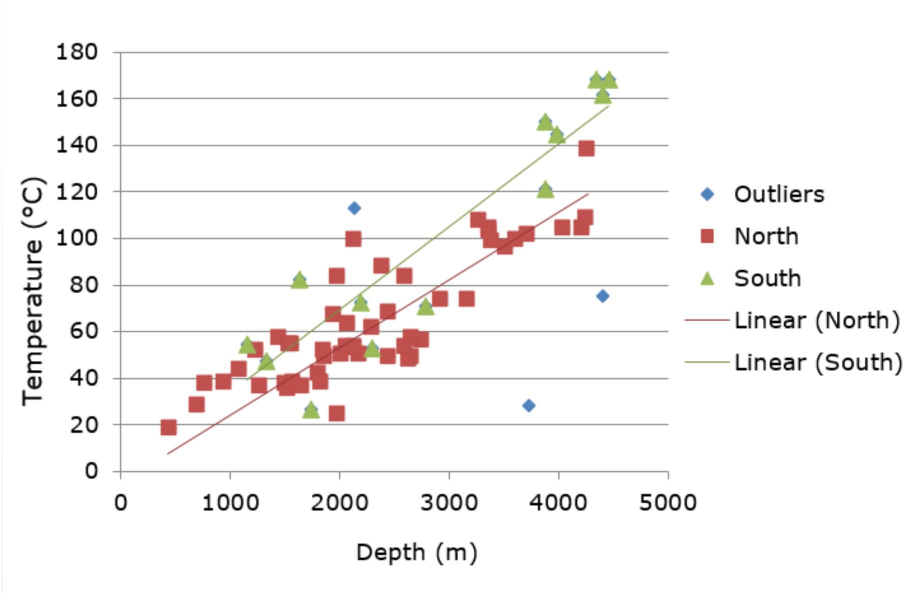
3. Actual temperature measurements at depth were compared to the predicted values and the differences identified.

4. Those points, where the difference exceeded 2 standard deviations, were excluded from the set of data ultimately mapped, being identified as anomalous. This does not mean that they are

invalid, rather that the QA/QC work necessary to confirm them is beyond the scope of this initiative.

5. Maps were developed based on the data, which was within 2 standard deviations of the depth-specific trend.

The following figure is a plot of the temperature with depth, showing 3 of the 67 available bottom hole temperatures available falling outside the standard deviation of 2 from the global trend. The 'North' subset of wells indicates wells drilled in the Northern Yukon Fold Complex (Peel Plateau and Eagle Plain) and a few along the Arctic Margin Basin. The 'South' subset of wells represents wells in the Western Canadian Sedimentary Basin (Liard Basin.)



4.2.2 Temperature Profile

The first step in following the Global Protocol was to estimate and model the temperature profile, heat flow and available heat of the Earth's crust down to a 5,000 metre depth. No measurements below the 4,000 to 5,000 metre interval were recorded so no attempt was made to interpolate values below 5,000m.

a. Build a Geographic Information Systems (GIS) database and split the Yukon into both NTS grid cells and 5'x5' grid cells with rock property and geological attributes.

This divided the Yukon into individual surface cells, with each cell representing a column from the surface to a depth of 5,000 m in 1,000 m intervals.

b. Create a sediment thickness (depth to basement) map.

c. Populate sediment thermal properties: thermal conductivity (K_S) and heat generation of sediment (A_S).

   Default properties given in the Global Protocol were used for these values.

   - K_S = 2.50 W/mK,
   - A_S = 1.00 µW/m^3

d. Populate basement thermal properties: thermal conductivity (K_B) and heat generation of basement rocks (A_B).

   Default properties given in the Global Protocol were used for these values.

   - K_B = 3.45 W/mK,
   - A_S = 2.65 µW/m^3

   For each 3D grid block crossing the sediment–basement contact, these values were calculated as the volume-weighted average of values for sediment and basement components.

e. Create surface temperature map using mean average annual surface air temperature.

f. Create surface heat flow map.

   For grid cells in which borehole temperature data was available, the surface heat flow was calculated from the product of the average thermal gradient to the deepest temperature data and the thermal conductivity of the sediment, minus half the heat generated within the sediment.

g. Derive temperature and heat flow at sediment-basement interface for $S < 4{,}000$ m and $S >$ 4,000 m, where S is the depth to the sediment-basement interface.

   The methods and equations as given in the Global Protocol were employed to complete this step.

h. Derive T at depth X, down to 5,000 m depth, where X is the midpoint between 1,000 m intervals.

The methods and equations as given in the Global Protocol were employed to complete this step. Note that the Global Protocol recommends calculating temperature to 10,000 m for Theoretical Potential and 6,500 m for Technical Potential. The Geothermal Resource Estimate Maps of the Yukon, however, present both of these to 5,000 m to reflect current realistic (economic) drilling capabilities.

4.2.3 Theoretical Potential

The next step involves estimating the Theoretical Potential of geothermal power in the crust down to a depth of 5,000 m. As noted above, this is a departure from the Global Protocol, which recommends estimating Theoretical Potential to 10,000 m.

a. Derive average temperature for each 1,000 m depth interval. Approximate by calculating temperature at mid-point of each interval.

   The methods and equations as given in the Global Protocol were employed to complete this step.

b. Assign density (ρ) and specific heat capacity (C_p) of interval.

   The methods and equations as given in the Global Protocol were employed to complete this step.

c. Derive volume of each grid cell (V_c). Note that volume varies slightly with latitude as the distance between lines of latitude change as you move north and south. Thus the surface area, and hence the volume of each 3D grid cell, varies slightly with latitude.

d. Calculate available heat for each depth interval in each cell (H).

   The methods and equations as given in the Global Protocol were employed to complete this step.

e. Derive theoretical potential power (P).

   The methods and equations as given in the Global Protocol were employed to complete this step.

Please note that the power estimated is a reflection of the data available at each depth. As such, a decrease in power with increasing depth may be observed and is likely indicative of limited data availability more so than an actual decrease of potential power.

4.2.4 Technical Potential

The final step was to estimate the Technical Potential of geothermal power in the crust down to a depth of 5,000 m. As noted above, this is a departure from the Global Protocol, which recommends estimating Technical Potential to 6,500 m.

Technical Potential is defined by the Global Protocol as "Theoretical Potential that can be extracted after consideration of currently 'insurmountable' technical limitations". Technical Potential provides a more realistic estimate of geothermal power potential using current technology, and considering access restrictions.

For the Technical Potential estimate, it was assumed that all grid blocks containing primary data are accessible for geothermal production, as availability of down hole temperature measurements demonstrates that the location has previously been accessed for exploration. The Technical Potential was estimated for low, medium and high recoverability factor (R) for the rock of 0.05, 0.14 and 0.20, respectively. Note that the 'low' value is a departure from the Global Protocol, which recommends a minimum R = 0.02.

Also note that while First Nations and National/Territorial Parks are protected, given the potential for geothermal to provide clean energy to northern and remote communities and reduce greenhouse gas emissions, these lands are recognized but not excluded from the assessment. Some National Parks and protected areas already have geothermal and other renewable developments and/or policies within their jurisdictions.

Please note that the power estimated is a reflection of the data available at each depth. As such, a decrease in power with increasing depth may be observed and is likely indicative of limited data availability more so than an actual decrease of potential power.

4.2.5 Primary Geothermal Exploration Areas

Although not required by the Global Protocol, this mapping project also provides a high level delineation of geothermal exploration areas. These regions, outlined in the figure below, summarize the cumulative association of key geological factors and the geothermal exploration results derived herein. Further classification of these potential exploration regions of moderate favourability into areas of high favourability was delineated from a probabilistic analysis of all input layers. Further detailed work is recommended to refine these results by region.

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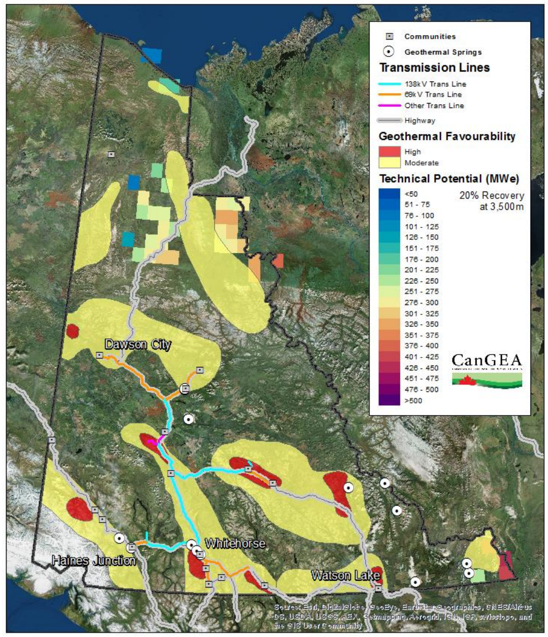
Primary Geothermal Exploration Areas



4.2.6 KML Formatting

The Global Protocol recommends that results be presented using common visualization and data architecture in accordance with previous geothermal potential maps, such as that produced for the United States in 2011 (www.google.org/egs).

a. The Geothermal Resource Estimate Maps of the Yukon were created using GIS software. All files contained in the geodatabase have been converted to KML format for visualization in Google Earth and presented in a format equivalent to that of the USA geothermal potential maps.

b. Layers for both the NTS and 5’x5’ grid versions include the following:
   - Estimated temperature at depth for Power Generation at 1 km intervals from 1,500 m to 4,500 m
   - Estimated temperature at depth for Direct Use purposes at 500 m and 750 m

- Grid blocks showing Theoretical Potential to 5 km
- Grid blocks showing Technical Potential to 5 km
- Level of confidence as either an Inferred or Indicated Resource, according to the Reporting Code
- Grid blocks showing geothermal gradient to 5 km
- Estimated depth to basement
- Grid blocks showing estimated conductivity to 5 km
- Grid blocks showing heat generation to 5 km
- Estimated heat flow at surface
- Geothermal favourability rating
- Land use including excluded zones, transmission lines/grid access and other major topographic/geological features

c. Layers will be available on the established CNGD (Canadian National Geothermal Database) web portal (http://www.cangea.ca/canadian-national-geothermal-database-and-resource-favourability-maps.html) as packages of downloadable KMZ files. The public will be able to view these files using the publicly available Google Earth program.

5.0 Summary Tables and Charts of Geothermal Potential

The value of Theoretical Potential depends on available geophysical data, while the derived Technical Potential is based on the current state of heat recovery and power conversion technology. As all of these will change over time, assumptions such as available heat, depth limits, recovery factor and net thermal efficiency will adjust, changing Theoretical and Technical estimates. Following the Global Protocol, we assumed that conduction is the dominant heat transfer mechanism and that thermal conductivity of sediment deeper than 4,000 m is the same as the basement. Where local data was not available, estimations and calculations relied on the algorithms and global means provided by the Global Protocol.

The tables and charts of estimates of geothermal potential and the data that underpin them are stored in GIS databases available through the CNGD web portal, a user-friendly interface for convenient access by all interested parties. These tables and charts include the following:

a. Temperature at depth data
b. Theoretical Potential estimates
c. Technical Potential estimates
d. Confidence data (in accordance with the Canadian Geothermal Code for Public Reporting)

6.0 Compliance with the Global Protocol and Reporting Code

This report and the data and calculations underpinning the Geothermal Resource Estimate Maps of the Yukon was prepared and endorsed by Dr. Graeme Beardsmore of Hot Dry Rocks Pty Ltd (Australia) as a "Competent Person", considered to be a "Qualified Person" under the Reporting Code. The Global Protocol respects the Reporting Code's underlying principles of 'transparency', 'materiality', and 'competence', and this project honours those principles by providing public access to all the underlying data, metadata, charts and tables used in the assessment of the Yukon's geothermal resources.

6.1 Canadian Geothermal Code for Public Reporting

The Geothermal Resource Estimate Maps of the Yukon include estimates of geothermal potential that could be categorized according to the terminology of the Australian and Canadian Geothermal Codes for Public Reporting.

The "Canadian Geothermal Code for Public Reporting" is designed to provide a level of consistency and transparency for the reporting of "Exploration Results", "Geothermal Resources" and "Geothermal Reserves". The primary data underpinning the Yukon maps are borehole temperatures, recorded within actual penetrations of the subsurface. The estimates of potential can therefore be classified as Resources rather than Exploration Results. "Indicated Resources" is used to classify estimates based directly on actual measured temperature data within a 3D grid cell, while "Inferred Resources" is used for estimates based on values extrapolated from actual bottom hole temperature measurements. None of the geothermal potential reported in the Geothermal Resource Estimate Maps of the Yukon can be classified as "Measured Resources" because fluid flow capacity has not currently been determined from any real data. Further analysis of individual well data would be required to determine if there could be an increase in confidence level to Measured Resources for any of the results.

Classification of Reserves requires economic assumptions unique to specific companies and projects, and is inappropriate at the scale of the Geothermal Resource Estimate Maps of the Yukon.

7.0 Data Limitations and Implications

The Yukon geothermal resource evaluation revealed a number of key findings and limitations of the available data. Key items are summarized below.

- Large areas of the Yukon were not available for incorporation into this study due to the lack of sufficient data across much of the Territory.

- While the reported resource estimates are substantial, the estimates are dominantly based on potential resources in the northeastern half and southeastern tip of the Yukon only, due to the data density from the oil and gas wells drilled in the Peel Plateau, Mackenzie Delta, and the Liard Basin.

- The Global Protocol is not suitable for incorporating data within volcanic and crystalline rock terrain. Therefore, areas that have been indicative of high potential for geothermal development, based on geological setting and previous evaluations, are not adequately reflected within this mapping study.

- Further evaluation of the oil and gas industry data would likely serve to increase the confidence in the resource estimates for the Yukon. Significant water production data exists within the industry. This could be combined with relevant thermal data to produce a “Measured” estimate of the geothermal potential of specific reservoirs, according to the Canada Geothermal Code for Public Reporting.

- There may be other industry information that would serve to increase the data coverage and add to the estimates for geothermal potential in the Yukon if it were made available or collected during future work, such as within the mineral exploration or water well drilling industries. This would also include estimates of sediment thickness over basement and/or metamorphic/igneous crystalline rock.

The overall result of these limitations is a significant underestimation of the geothermal resource potential in the Yukon, in our opinion.

Project Team

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Glossary

Enhanced Geothermal Systems (EGS)- a production scheme extracting hot fluid from the ground and passing it through a power conversion plant before re-injecting the cooled fluid back underground where it is reheated by the rock in a continuous cycle through an artificially enhanced underground heat exchanger. EGS is not a distinct play-type, but rather a geothermal exploitation technique. The term is often misused in literature.

Geographic Information Systems (GIS)- an organized collection of computer hardware, software, and geographic data designed to efficiently capture, store, manage, analyze, manipulate and display all forms of geographically referenced information.

Indicated Geothermal Resource- is that part of a Geothermal Resource which has been demonstrated to exist through direct measurements that indicate temperature and dimensions so that recoverable thermal energy (MWth-years) can be estimated with a reasonable level of confidence.

Inferred Geothermal Resource- is that part of a Geothermal Resource for which recoverable thermal energy (MWth-years) can be estimated only with a low level of confidence.

Theoretical Potential- an estimate of "the physically usable energy supply over a certain time span in a given region. It is defined solely by the physical limits of use and thus marks the upper limit of the theoretically realizable energy supply contribution" [8].

Technical Potential- the fraction of the Theoretical Potential that can be used under the existing technical restrictions…structural and ecologic restrictions as well as legal and regulatory allowances" [9].

[8] Rybach, 2010
[9] Rybach, 2010

Symbols

ρ density
A_B heat generation of basement rocks (W/m^3)
A_S heat generation of sediment (W/m^3)
C_p specific heat capacity (J/kgK)
H total available thermal energy (EJ)
K_S thermal conductivity of sediment (W/mK)
K_B thermal conductivity of basement (W/mK)
P Theoretical Potential
P_T Technical Potential
R Recoverability factor
V_c volume of each 5’ x 5’ or NTS x 1,000 m cell (m^3)

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Appendix I: Data Sources

Data	Source	Website	Date Retrieved
Yukon 5'x5' Grid	(created in-house)	N/A	N/A
Yukon NTS Grid	NRCan	ftp://ftp2.cits.rncan.gc.ca/pub/index/nts_snrc.zip	May 2015
Depth to Basement	Geological Atlas of the WCSB	http://www.ags.gov.ab.ca/publications/wcsb_atlas/atlas.html	June 2015
	NRCan – DNAG Vol G2	http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=134069	July 2015
			July 2015
Heat Generation of Sediment	Geological Atlas of the WCSB	http://www.ags.gov.ab.ca/publications/wcsb_atlas/atlas.html	21-Sep-13
Heat Generation of Basement Rocks	Geological Atlas of the WCSB	http://www.ags.gov.ab.ca/publications/wcsb_atlas/atlas.html	21-Sep-13
Mean Average Annual Surface Air Temp	Environment Canada	http://www.ec.gc.ca/dccha-ahccd/default.asp?lang=En&n=1EEECD01-1	July 2015
	Weather Network via Farmzone	http://www.farmzone.com	June 2015
Temperature Borehole Data	Geothermal Data Compilation	http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/58d02b6c-deea-5f45-aef5-3c162b46666b.html	July 2015
	NABH	http://www.ncdc.noaa.gov/paleo/borehole/nam.html	July 2015
Regional Geology	Yukon Geological Survey	http://www.geology.gov.yk.ca/databases_gis.html	June 2015
Yukon Boundary	NRCan	http://www.nrcan.gc.ca/earth-sciences/geomatics/canada-lands-surveys/11092	May 2015

Aboriginal Lands	GeoBase	http://www.geobase.ca/geobase/en/search.do?produit=alta&language=en	Sept 2015
National Parks	NRCan	http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/ef60d323-8b11-5908-b06b-caafb197563d.html	May 2015
Territorial Parks, Ecological Reserves & Protected Areas	NRCan and Yukon Gov't	http://mapservices.gov.yk.ca/GeoYukon/SL/ http://www.nrcan.gc.ca/earth-sciences/geomatics/canada-lands-surveys/11092	May 2015
Transmission Lines	Yukon Energy	http://yukonenergy.ca/	Dec 2015

Appendix II: List of all Yukon Geothermal Resource Estimate Maps- for both NTS and 5'x5' versions

Map Title
Surface Temperature (°C)
Temperature (°C) at 500m
Temperature (°C) at 750m
Temperature (°C) at 1,500m
Temperature (°C) at 2,500m
Temperature (°C) at 3,500m
Temperature (°C) at 4,500m
Estimated Technical Potential (MWe) between 1,000 – 2,000m; 5% Recoverability
Estimated Technical Potential (MWe) between 2,000 – 3,000m; 5% Recoverability
Estimated Technical Potential (MWe) between 3,000 – 4,000m; 5% Recoverability
Estimated Technical Potential (MWe) between 4,000 – 5,000m; 5% Recoverability
Estimated Technical Potential (MWe) between 1,000 – 2,000m; 14% Recoverability
Estimated Technical Potential (MWe) between 2,000 – 3,000m; 14% Recoverability
Estimated Technical Potential (MWe) between 3,000 – 4,000m; 14% Recoverability
Estimated Technical Potential (MWe) between 4,000 – 5,000m; 14% Recoverability
Estimated Technical Potential (MWe) between 1,000 – 2,000m; 20% Recoverability
Estimated Technical Potential (MWe) between 2,000 – 3,000m; 20% Recoverability
Estimated Technical Potential (MWe) between 3,000 – 4,000m; 20% Recoverability
Estimated Technical Potential (MWe) between 4,000 – 5,000m; 20% Recoverability
Estimated Theoretical Potential (MWe) between 1,000 – 2,000m
Estimated Theoretical Potential (MWe) between 2,000 – 3,000m
Estimated Theoretical Potential (MWe) between 3,000 – 4,000m
Estimated Theoretical Potential (MWe) between 4,000 – 5,000m
Indicated vs Inferred Resources – 1,500m
Indicated vs Inferred Resources – 2,500m
Indicated vs Inferred Resources – 3,500m
Indicated vs Inferred Resources – 4,500m

Average Geothermal Gradient (K/km) at between 1,000 – 2,000m
Average Geothermal Gradient (K/km) at between 2,000 – 3,000m
Average Geothermal Gradient (K/km) at between 3,000 – 4,000m
Average Geothermal Gradient (K/km) at between 4,000 – 5,000m
Depth to Basement (m)
Average Estimated Conductivity W/(m • K) between 1,000 – 2,000m
Average Estimated Conductivity W/(m • K) between 2,000 – 3,000m
Average Estimated Conductivity W/(m • K) between 3,000 – 4,000m
Average Estimated Conductivity W/(m • K) between 4,000 – 5,000m
Average Estimated Heat Generation (EJ) between 1,000 – 2,000m
Average Estimated Heat Generation (EJ) between 2,000 – 3,000m
Average Estimated Heat Generation (EJ) between 3,000 – 4,000m
Average Estimated Heat Generation (EJ) between 4,000 – 5,000m
Estimated Heat Flow (mW/m^2) at Surface
Primary Geothermal Exploration Areas