Favourability Map of British Columbia Geothermal Resources

by

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Abstract

British Columbia’s internal demand for power and demand from export operations is increasing the need for power generation in the province. Moreover, the transition to a low carbon economy stipulates that power supply must be from renewable and low emission sources. Geothermal energy offers significant benefits to British Columbia which hosts Canada’s best geothermal resources associated with the Pacific Ring of Fire along the Coast Mountain Range.

The objective of this work was to visualize and compare the spatial distribution of geothermal resources, transmission infrastructure, and power markets in BC. Using ArcGIS, these factors were combined into a map identifying the most favourable regions for geothermal development in the province. Multi-criteria evaluation of 10 evidence layers was completed in a knowledge-driven model. Publicly available data for temperature gradient, heat flow, volcanic centers, geothermometry, hot springs, geology, faults, and earthquake indicators comprised the resource factor map. Evidence layers in the market and infrastructure factor map included: distance to transmission, regional pricing, and population density. Evidence layers were assigned weights based on a judgment of their importance to geothermal favourability using the Analytical Hierarchy Process.

The favourability map builds on the 1992 Geothermal Resources Map of British Columbia by incorporating new data, and applying spatial buffers based on studies from producing geothermal fields from around the world. The research

has demonstrated how economic and infrastructure factors can be integrated into the evaluation of a region’s geothermal resources.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

2008 LTAP: 2008 Long-Term Acquisition Plan

AHP: Analytical Hierarchy Process

ASTER: Advanced Spaceborne Thermal Emission and Reflection

ATC: Available Transfer Capacity

BC MEMPR: British Columbia Ministry of Energy Mines and Petroleum Resources

BC: British Columbia

BCGS: British Columbia Geological Survey

BCTC: British Columbia Transmission Corporation

BCUC: British Columbia Utilities Commission

CI: Consistency Index

CIFT: Cost of Incremental Firm Transmission

CR: Consistency Ratio

DEM: Digital Elevation Model

EBF: Evidential Belief Function

EGS: Engineered (or Enhanced) Geothermal Systems

FIT: Feed-in-Tariff

GIS: Geographic Information Systems

GM-GRE: GIS Model for Geothermal Resource Exploration

GSC: Geological Survey of Canada

HDR: Hot Dry Rock

HFR: Hot Fractured Rock

IDRISI: Integrated Geographic Information System

IFHC: International Heat Flow Commission

InSAR: Interferometric Synthetic Aperture Radar

IPP: Independent Power Producer

LIDAR: Light Detection and Ranging

MCE: Multi-Criteria Evaluation

MIT: Massachusetts Institute of Technology

Mt.: Mount

NE: Northeast

NNW: North-northwest

RI: Random Index

RPS: Renewable Portfolio Standard

SOP: Standard Offer Program

SRTM: Shuttle Radar Topography Mission

U.S.A.: United States of America

USGS: United States Geological Survey

WCSB: Western Canada Sedimentary Basin

WNW: West-northwest

List of Symbols

~: Approximately

<: Less than

>: Greater than

±: Plus or minus

≤: Less than or equal to

≥: Greater than or equal to

β: Correction factor for the cation geothermometer

As: Arsenic

B: Boron

Ca: Calcium

Cd: Cadmium

CH_4: Methane

CO_2: Carbon dioxide

D: Depth (m)

Fe: Iron

H_2: Hydrogen

H_2S: Hydrogen sulphide

Hg: Mercury

K: Kelvin

K: Potassium

K: Thermal conductivity (W/mK)

K-Ar: Potassium-Argon

Li: Lithium

Mg: Magnesium

Mn: Manganese

n: Order of matrix

N_2: Nitrogen

Na: Sodium

Na-K-Ca: Sodium-Potassium-Calcium (cation)

NH_3: Ammonia

Pb: Lead

SiO_2: Silica

T: Temperature (°C or K)

∇T: Temperature gradient (°C/km)

Zn: Zinc

Q: Heat flow (mW/m^2)

λ_{max}: Largest eigenvalue

List of Units

cents/kWh: Cents per kilowatt hour
^oC: Degrees Celsius
^oF: Degrees Fahrenheit
kg/MWh: Kilograms per megawatt hour
km: Kilometre
km^2/Twhr/yr: square kilometre per terawatt hour per year
kV: Kilovolt
m: meter
Ma: Millions of years ago
mg/L: Milligrams per Litre
mW/m^2: Milliwatts per square meter
MW: Megawatt
MWe: Megawatt electric
MWt: Megawatt thermal
g/kg: Grams per kilogram
GWh: Gigawatt hours

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1 Introduction

British Columbia is currently a net importer of electricity, relying on other jurisdictions for about 10% of our electricity supply (BC MEMPR, 2007). Increasing population and economic growth is increasingly driving demand for electricity within the province. The latest forecasts predict demand to grow by 20-35% over the next 20 years without taking into account energy efficiency measures (BC Hydro, 2009). The Province's present energy policy goals aim to achieve electricity self-sufficiency by 2016 and to become a clean energy exporter to other regions (BC MEMPR, 2010a). Both of these goals will lead to an increase in the need for renewable power since hydropower has likely reached a limit.

Concerns over climate change, dwindling fossil fuel supplies, and energy independence are causing a shift towards a low carbon economy. To this end, the Clean Energy Act of British Columbia (BC MEMPR, 2010a) stipulates that 93% of electricity generation must have net zero emissions. Renewable energy technologies such as geothermal energy have the potential to contribute to British Columbia's sustainable energy mix of sources with zero emissions.

When compared to other energy sources (both renewable and non-renewable), geothermal energy has many benefits, including: extremely low emissions, low environmental impact, high capacity factor, base-load, low surface footprint, and low levelized energy cost.

Geothermal energy in Canada is mainly in the province of British Columbia where high geothermal gradients exist associated with the Pacific Ring of Fire along the Coast Mountain Range. Developments in lower temperature power generation plants, and the use of Engineered Geothermal Systems (EGS) technologies may extend the geothermal potential into other regions of the province and perhaps, even across Canada.

To assess the geothermal potential of a region, it is necessary to understand the spatial distribution of relevant technical, economic and social factors. Geographic Information Systems (GIS) can be used to visualize spatial data and combine various geospatial datasets to create "intelligent" maps. Tools available through GIS allow one to manage, manipulate, display, and analyze data in extremely creative ways.

1.1 Research Question

The critical research questions in this thesis are "Where are the most favourable geothermal resources located in British Columbia?" and, "What is the spatial relationship between areas of high geothermal potential, and infrastructure and energy markets?" By analyzing the spatial relationship of the resource, infrastructure, and market factors, the opportunities and challenges for geothermal power can be explored.

1.2 Objectives

The objective of this work was to create a favourability map of BC geothermal resources based on data related to the resource, infrastructure and market. The data set contained information related to the temperature and permeability of the resource, the distance to and quality of the existing infrastructure, and the distance to and types of energy markets. A map was created to facilitate visualization and understanding of the spatial distribution of factors affecting the geothermal energy potential of a region. This work informs stakeholders, including geothermal developers, government regulators and proponents, utility companies, land-use planners, local communities, and other parties interested in the most favourable areas for geothermal development.

1.3 Methods

Factors that contribute to geothermal favourability are grouped into three separate layers, with the resource layer sub-divided into two indicator groups (Figure 1). Chapter 4 reviews the resource factor map comprised of multiple temperature and permeability indicators. Chapter 5 reviews the components of the market & infrastructure factor map.

The data is compiled and transformed in ArcGIS and a series of evidence layers are produced (temperature gradient, volcanology, etc.). These individual layers are combined into Factor Maps using the multi-criteria evaluation in GIS.

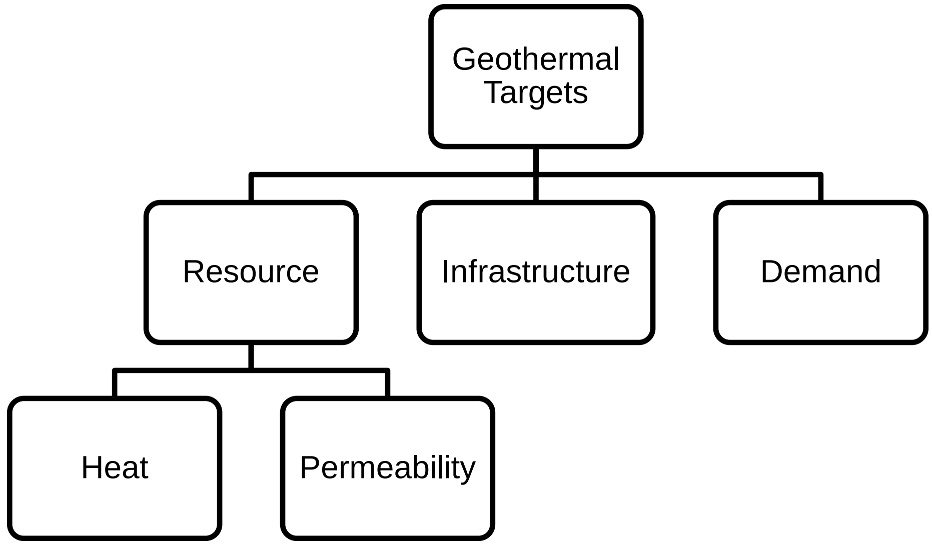

Figure 1: Favourability map components

2 Geothermal Energy

Quite simply, geothermal energy is "energy from the Earth". The heat source comprises both primordial heat from the formation of the Earth, and heat from the decay of natural radioisotopes contained at depth (Rybach & Mongillo, 2006). The Earth's core is molten with an average temperature of ~4000^{o}C, and this heat is continuously being lost at the surface to the atmosphere creating an increase in temperature with depth called the geothermal gradient. The transfer of heat from the core occurs primarily through conduction through solid rock and secondarily through convection in areas with fluid interaction (i.e. water, magma, salt diapirs[1]).

While the Earth's subsurface heat is ubiquitous and essentially inexhaustible, the ability to produce geothermal energy requires unique circumstances. Firstly, there must be a concentration of the Earth's heat which most commonly exists in areas near cooling magma bodies. Secondly, this heat must be located at depths shallow enough (< 5 km but generally ~3 km with economic constraints) to be accessed by drilling. Finally, there must be a demand for geothermal energy such that the economic expenditures in developing the project can be justified.

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[1] A geological intrusion in which a more mobile, ductile, and deformable material is forced into more brittle overlying rocks.

[2] "delta T" refers to the temperature difference between the geothermal fluid and the rejection temperature, higher values of delta T increase the efficiency of a power plant.

[3] Parasitic load refers to the energy required to move the fluid out of and back into the resource after extracting the heat content.

[4] Available at http://www.geo.lsa.umich.edu/clihttp://www.geo.lsa.umich.edu/climate/NAM.html

Geologic processes, specifically plate tectonics, control the concentration of the Earth's heat. Volcanic activity and the presence of magma near the surface occurs at tectonic plate boundaries and over mantle hot spots of volcanism which explains the concentration of geothermal energy production in regions such as the Pacific Ring of Fire (Bertani, 2010).

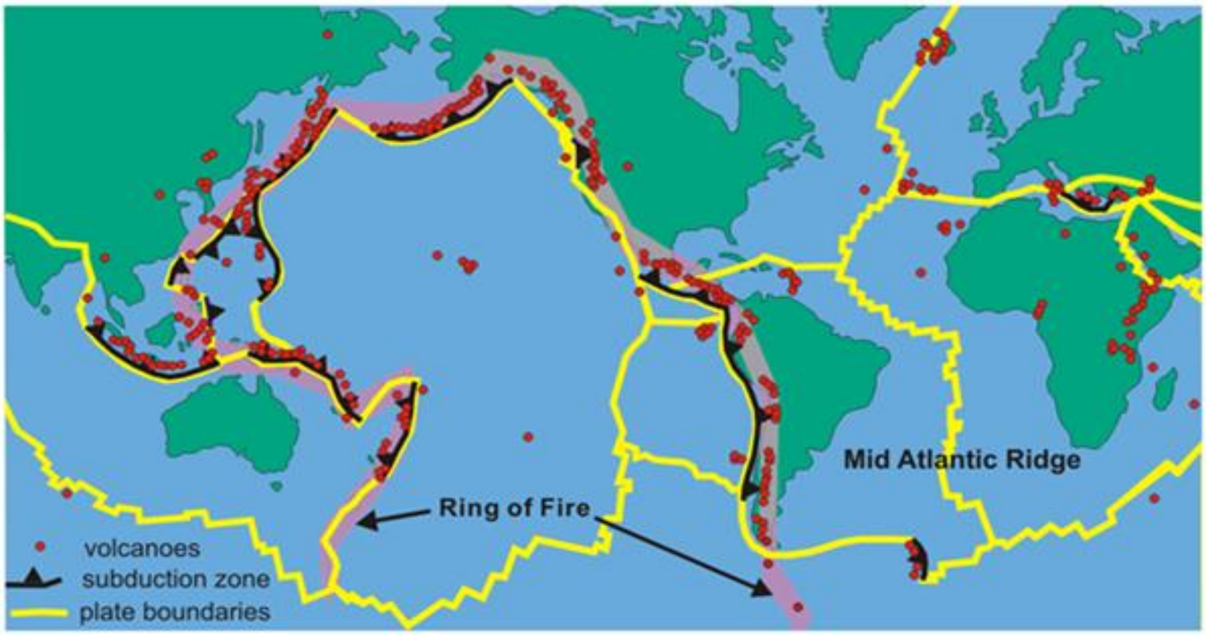

Figure 2: Volcanoes, subduction zones, and plate boundaries of the world showing the Ring of Fire. Reproduced with the permission of Natural Resources Canada 2010, courtesy of the Geological Survey of Canada (C.J. Hickson, 2005).

Geothermal energy utilization began over a century ago in 1904 at Larderello, Italy (Fridleifsson, 2001). Today the total world installed capacity is 10,715 MW contributing over 67,246 GWh to the global energy mix (Bertani, 2010). Over 65% of the world's geothermal power capacity is located in three countries: the United States leads with 3,903 MW of installed capacity followed by the Philippines (1,904 MW) and Indonesia (1,197 MW) (Bertani, 2010). As the demand for renewable power supply increases and geothermal energy technology improves, countries in different geologic settings are now utilizing unconventional (i.e. EGS and lower temperatures) resources for geothermal power generation.

2.1 Types of Geothermal Resources

Geothermal resources are classified into different types by the heat source and hydraulic nature of the system. All geothermal systems have three basic requirements: (1) a heat source, (2) permeability, and (3) a carrier fluid. The heat is transferred from the source by a carrier fluid to the surface through faults, fractures, and permeable lithologic units.

2.1.1 Hydrothermal

Hydrothermal reservoirs are the most common and economically feasible geothermal resources (Barbier, 2002). Hydrothermal-type geothermal systems are located in areas where intrusions of magma into the continental crust have created convective circulation of groundwater. Convective geothermal systems generally do not reach temperatures of 200^{o}C or higher without an upper crustal magmatic heat source, however notable exceptions do exist. For example, in the Basin and Range geological province of the U.S.A., the extensional tectonic setting creates deep-penetrating normal faults that provide pathways for meteoric water to be heated at depth (Coolbaugh, Arehart, Faulds, & Garside, 2005).

The carrier fluid of a hydrothermal system can be either water or vapour, the latter however are relatively rare and only found in geothermal reservoirs of very high temperatures (250 to 320 ^{o}C), well in excess of the boiling point of water (Rowley, 1982). The world's first geothermal reservoir in Larderello, Italy and the world's largest geothermal reservoir at the Geysers in California, U.S.A. are both vapour-dominated reservoirs. Vapour-dominated hydrothermal reservoirs are favourable because of their higher energy content per unit fluid mass (Barbier, 2002), and are considered to be the "highest-grade" geothermal resource.

2.1.2 Engineered Geothermal Systems

Engineered or Enhanced Geothermal Systems (EGS) have been heralded as the future of geothermal energy (Tester, et al., 2006). Terminology used to describe these systems has evolved from Hot Dry Rock (HDR), Hot Fractured Rock (HFR), and more recently, Engineered or Enhanced Geothermal Systems (EGS). EGS more accurately describes systems in which water is present in the formation, but other elements such as permeability are absent. In principle, EGS resources extend the geothermal resource base to the entire world. Economically favourable EGS projects are located in areas that are easily accessible, with elevated heat flow and sufficient water resources for project operations (Tester, et al., 2006). The resource temperature can be enhanced by drilling to greater depths (>5 km). Hydraulic fracturing of the reservoir or chemical stimulation (in carbonate formations) can enhance permeability. And, a carrier fluid (water) can be injected into the reservoir to carry the heat to surface. The enhancement of these factors allow for wider-scale application of geothermal technology.

For some, the term EGS can be applied to any site that requires engineering or enhancement, which suggests that nearly all geothermal projects are “EGS”. In general, EGS involves pumping high-pressure water down an injection well to stimulate a fracture network, creating artificial permeability. While traveling through the fracture network, the water captures heat from the surrounding formation and is pumped back to surface where the heat is extracted and converted to energy.

An MIT-led study (Tester, et al., 2006) suggests that EGS can provide 100 GWe of energy to the U.S.A. in the next 50 years. To realize this incredible potential, significant technical and economic challenges must be overcome. To date, EGS experiments have successfully ‘proven the concept’ and been able to generate power. But after over 25 years of research and development, the Soultz-Sous-Forets project on the border of Germany and France generates only 1.5 MWe (Gerard, Genter, Kohl, Lutz, Rose, & Rummel, 2006).

Research continues into many aspects of EGS including the issue of induced seismicity caused by injecting water into the reservoir. The U.S. Department of Energy recently awarded over $80 million for EGS research and development, and an additional $51 million for EGS demonstration projects (U.S. Department of Energy, 2009).

Germany has successfully deployed EGS with 3 plants producing 6.6 MWe, 2 of the plants are combined with district heating systems that produce an additional 55.0 MWt (Schellschmidt et al., 2010). Australia is aggressively developing its Hot Dry Rock resources located north of Adelaide- a granitic structure reputed to be the hottest rock in the world at equivalent depths. Development involves drilling wells to 5 km depth, stimulating the reservoir and then circulating borrowed fluids. The technique has been demonstrated at the Cooper Basin project, however economic flow rates have yet to be achieved (Geodynamics Ltd., 2009).

2.1.3 Other Resources: Geopressured, Magma, Off-shore, Co-production

As demand for renewable energy increases and technology improves, other methods to harness geothermal energy may develop into commercial technologies. These include: geopressured energy, magma energy, Ocean/off-shore geothermal energy, and co-production from oil and gas.

Geopressured fluids are located in sedimentary basins at a depth of ~4 to 6 km where hot water has been trapped at the time of deposition and is now at pressures greater than hydrostatic. These fields could potentially produce energy from the pressurized hot water, hydraulic energy from the high pressure, and energy from associated methane gas (Barbier, 2002).

The high temperature of magma makes it an attractive target for geothermal power generation. The challenges are: identifying the location of magma bodies within the crust more accurately to allow for better drill targeting, developing drilling equipment able to operate at extreme temperatures (currently limited to ~250^{o}C), and providing a heat extraction technology that justifies the significant development costs (Barbier, 2002). The Iceland Deep Drilling Project drilled into rhyolitic magma at a depth of 2,104 m (Fridleifsson, et al., 2010) and dacitic magma but geothermal production was not pursued due to issues of well control.

Hydrothermal vents located along oceanic ridges emit temperatures of about 300^{o}C. If only 1% of known hydrothermal vents were exploited using a binary cycle power plant housed inside a submarine it is estimated that 130,000 MW of power could be generated (Hiriart, Prol-Ledesma, Alcocer, & Espindola, 2010). However, hydrothermal vents are located 100s of kilometers off-shore where transmission development would be extremely costly.

Deep-sea geothermal resources accessed by drilling have also been postulated as a future geothermal resource. Shnell (2009) suggests power could be generated at the ocean floor by a self-contained, submersible, remote-controlled, geothermal powered electric generating station.

In petroleum wells that have been abandoned, or that have a large water fraction, there is the opportunity to generate power from the hot water. Additional drilling would not be required for co-production, however because of the smaller diameter and lower flow rates of typical oil and gas wells, the heat losses from the bottom to the top of the well and in the un-insulated surface equipment are un-suitable for geothermal production in many cases. This technology is being implemented in Swan Hills, Alberta where 75^{o}C water from mature oil wells will be used to generate geothermal electricity (Borealis Geopower, 2010).

2.2 Applications of Geothermal Resources

Geothermal resources are divided into two categories: direct use and electrical power generation. The division is primarily based on the resource temperature, with conventional electrical power production from fluids at temperatures usually above 150^{o}C. It is possible however to produce electrical power from lower temperature resources using a binary cycle process. The lowest known temperature from which geothermal electricity is produced is in Chena, Alaska where 74^{o}C (165^{o}F) discharge waters are used in a binary cycle power plant (Erkan et al, 2007). The Chena plant which produces 730 kW (gross) is unique in that it is located in Alaska and 4^{o}C cooling water is available from a stream to yield a high enough "delta T"[2] (Lund, Gawell, Boyd, & Jennejohn, 2010). At the lower end of the temperature scale (from ~5 to 85^{o}C), geothermal heat can be used for direct use applications or to supply heat pumps.

The application of a geothermal resource is mainly a function of temperature; however site-specific factors (climate, economics, and technology) can shift the temperature boundaries of each type in either direction. Cascaded geothermal resources that utilize geothermal fluids for multiple applications are

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[2] "delta T" refers to the temperature difference between the geothermal fluid and the rejection temperature, higher values of delta T increase the efficiency of a power plant.

becoming more common and greatly enhance the economics of a project (Lund et al., 2010).

2.2.1 Direct Use

In 2010, the worldwide installed capacity of direct use geothermal systems was 50,583 MWt with ground source heat pumps or GeoExchange systems accounting for about half the total (Lund, Freeston, & Boyd, 2010). In Canada, the installed capacity is 1,126 MWt and annual use totals 2,465 GWh/year (Lund, Freeston, & Boyd, 2010).

Geothermal heat has many applications, including: space heating for domestic and agricultural purposes, bathing & swimming, snow melting, etc. An example of successful direct use in Canada is from the closed Springhill coal mine in Nova Scotia where 18^{o}C waters extracted from the underground mine workings are used to heat and cool an industrial park (Jessop, 1995). Similar projects have been examined in BC, specifically at the Bluebell Mine near Riondel, BC (Desrochers, 1992) and at the Britannia Mine north of Vancouver (Meech et al., 2006). The City of Yellowknife is currently investigating the potential for direct use from the Con Mine (Natural Resources Canada, 2010).

2.2.2 Power Generation

Power generation begins with the drilling of wells into a geothermal reservoir. The wells target zones of permeability where fluid carries heat from the hot reservoir up a production well to the earth’s surface. If the pressure in the reservoir is high enough, the wells are self-flowing. If adequate pressure does not exist, then the fluids can be pumped, but this increases the “parasitic load”[3] of the power plant. Once at surface, the fluid passes through a conventional steam and/or gas turbine to generate power. Finally, the fluid is re-injected back into the subsurface via injection wells.

Three types of power plants are used for geothermal power production: (1) flash-steam, (2) dry-steam, and (3) binary cycle. Combined cycle power plants that utilize flash plants for the “topping cycle” and binary plants for the “bottoming cycle” are also in use to maximize the resource extraction. In a flash-steam plant, the carrier fluid is “flashed” from water to steam at surface. In a dry-steam plant, the fluid is at such high temperatures it is already in vapour form and can directly turn a turbine. Dry-steam plants are unique to only four geothermal fields in the world (in Italy, U.S.A., Indonesia, and Japan) that produce natural steam (Barbier, 2002). Binary cycle power plants are the most commonly used geothermal power plants today (Bertani, 2010). In a binary cycle plant, geothermal waters heat a secondary fluid with a low boiling point (e.g. isobutene or isopentane) through a suitable heat exchanger, which in turn flashes to a vapour to drive turbine (different from a steam turbine).

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[3] Parasitic load refers to the energy required to move the fluid out of and back into the resource after extracting the heat content.

2.3 Benefits of Geothermal Energy

The many benefits of geothermal energy include reliability and provision of base-load power. The capacity factor of geothermal power plants is extremely high at ~90% meaning geothermal power plants operate close to their nameplate capacity unlike solar and wind. Geothermal energy can contribute to a sustainable energy mix through diversification of energy sources and can act to complement the intermittent nature of other energy sources. Geothermal energy has a predictable long-term production cost independent of the fossil fuel markets.

Because geothermal energy utilizes an underground heat exchanger, it has an extremely low land-use impact compared with other forms of power generation. In a study to predict the land area required for power production in the U.S.A. by 2030, geothermal power required only 1.0 to 13.9 km^2/TWhr/yr (second lowest after nuclear), compared to 433-654 km^2/TWhr/yr for biomass and 27.5-99.3 km^2/TWhr/yr for liquid fuels (McDonald, Fargione, Kiesecker, Miller, & Powell, 2009).

Geothermal energy is considered renewable since the Earth's near-surface heat is constantly being replenished and fluids are recharged both naturally and through re-injection. However, if economic exploitation of geothermal fluids exceeds the natural replenishment rate there may be depletion in the heat and/or fluid content of the reservoir. Numerical modeling shows that after production ceases, practical (e.g. 95%) replenishment will occur on a time scale similar to that of the production stage (Rybach & Mongillo, 2006). In economic models, geothermal projects are often studied for an arbitrary period of 20-30 years (Barbier, 2002) however plants such as Larderello in Italy that has been operating since 1904 demonstrates that if managed properly, a geothermal resource can be productive for much longer periods of time.

2.4 Environmental Impacts of Geothermal Energy

The environmental impacts of geothermal energy are minimal compared to other sources, particularly fossil fuel types. However minimal, the impacts of geothermal that do exist must be understood and mitigated. The main effects occur from the discharge of gas and water that contains high concentrations of elements (metals and salts) leading to chemical pollution and possible biological effects. Less common impacts include physical effects due to water extraction, thermal changes, and noise.

Both natural geothermal features (e.g. fumaroles) and geothermal wells emit CO_2, H_2S, NH_3, N_2, H_2, and CH_4 gases that are generally found at concentrations of 3 to 47 g/kg as non-condensable gases in steam (Barbier, 2002). These gases may be emitted to the atmosphere in flash or dry steam power plants.

Geothermal waters often contain high concentrations of elements and are sometimes referred to as brines. The composition of fluids varies significantly depending on the geologic and meteorological setting; however common pollutants in geothermal liquids are H_2S, B, As, Hg, Pb, Cd, Fe, Zn, and Mn (Kristmannsdottir & Armannsson, 2003).

Using binary cycle power plants reduces the amount of chemical pollution from geothermal power by eliminating the venting of gases into the atmosphere as well as surface discharge of liquids. While it is expected that a geothermal power project in BC would use a binary cycle plant and thus would not emit any steam, it is plausible that a flash steam plant might be built in the future. Under these circumstances, fluids discharged from the geothermal site would have to be characterized to ensure they meet provincial regulatory requirements. In most cases, the fluids are treated prior to discharge to precipitate heavy metals. The sludge must then be dealt with in an acceptable manner.

In comparison to other energy sources, the emissions of CO_2 from geothermal power plants are minute (Table 1) so this choice of energy supply is a leading alternative to assist in addressing Climate Change issues.

Table 1: CO_2 emissions by energy source (after Reed & Renner, 1995)

Energy Source	CO_2 emissions (kg/MWh)
Coal	990
Petroleum	839
Natural Gas	540
Geothermal	0.48

Withdrawing fluids from a geothermal reservoir at rates higher than natural recharge, may cause physical effects such as changes in surface manifestations such as hot springs, lowering of the groundwater table, land subsidence, and induced seismicity (Gupta & Roy, 2007). While the fluid is typically recycled back into the resource, drawdown of the water table is likely because of volume changes in the fluid after heat extraction.

2.5 Exploration

Geothermal systems occur as a variety of resource types and in a variety of geologic settings. Geothermal “plays” include: hydrothermal (magmatic and tectonic sources), hot-sedimentary aquifers, and EGS.

Exploration for high-temperature geothermal resources has traditionally involved geological, geophysical, and geochemical techniques aimed at identifying thermal anomalies, geothermal fluids, and permeability. Delineation begins with regional reconnaissance, prospect identification, and project appraisal (Monastero & Coolbaugh, 2007).

Initially, discovery of a geothermal system occurred because of surface manifestations such as hot springs, geysers, fumaroles, etc. The challenge today is to find “blind” geothermal resources, (i.e., sites that don’t show surface manifestations of geothermal activity). Examples of “blind” geothermal systems include sites in Nevada, U.S.A.: Desert Peak, Blue Mountain, Soda Lake, Stillwater, and Fish Lake Valley. These systems were found by serendipity while drilling for other purposes such as oil and gas or mineral exploration (Coolbaugh, Arehart, Faulds, & Garside, 2005).

According to Coolbaugh et al. (2005) “many features, including the presence of active faults, recent volcanic activity, earthquakes, high gravity gradients, and high temperature gradients, are useful for predicting geothermal activity and thus the presence of blind geothermal systems, but none of these features are perfect in terms of their uniqueness or, in the case of drilling, their cost effectiveness.”

2.6 Geothermal Energy in Western Canada

In Canada, the most-obvious geothermal resources are thermal anomalies associated with Quaternary volcanic belts (i.e. Garibaldi, Anahim, and Stikine belts). Within these belts, volcanic centers with a salic magma volume greater than 5 km^3 (Souther, 1980) are the most likely to contain a geothermal resource.

Moderate-grade geothermal resources may also be found associated with deep-circulating fluids along major faults such as those in the Rocky Mountain Trench similar to the resources in the Basin and Range geologic province centered in the state of Nevada.

In the Western Canada Sedimentary Basin (WCSB) which extends into northeast British Columbia from Alberta the insulating effect of thick sedimentary cover has created moderate geothermal gradients (up to 54^{o}C/km) This lower-grade heat resource is estimated from an abundance of well data from oil and gas wells, namely bottom hole temperatures (Majorowicz & Grasby, 2010) and (Arianpoo, 2009).

South-central British Columbia is a second region considered to contain geothermal resources. Geothermal gradients of 54^{o}C/km have been measured in the Coryell Syenite, which has been investigated as a possible site for an EGS target (Fairbank & Faulkner, 1992).

2.6.1 Previous Work

Systematic evaluation of geothermal resources in Canada began in 1973 (Souther, 1980) in response to the worldwide oil crisis of the time; a formal program operated for ten years, from 1st April 1976 to 31st March 1986 (Jessop, 2008a). Principal investigators have been Jessop, Souther, Sadlier-Brown, Fairbank, Ghomshei, and more recently, Grasby. The initial focus of the federal government-funded program was in western Canada where volcanic terrain and hot springs provided targets for exploration that eventually led to significant work in the Garibaldi Volcanic belt (e.g., Mt. Meager and Mt. Cayley).

The first geothermal demonstration project in Canada was conducted at the University of Regina in the late 1970's in which a well was drilled to a depth of 2,214 m. A drawdown test suggested 3.5 MW of thermal power was available based on estimated fluid flow rates at ~60°C. However, the building to which the well was meant to be connected was never constructed and the well could only be used as a research facility (Jessop, 2008a).

To date, a small number of investigations into the geothermal potential in Canada have been undertaken, mostly in British Columbia. Through the National Geothermal Energy Program, the town of Summerland, BC investigated the potential to harness geothermal resources in the area for greenhouse applications (Jessop, 2008a). The community of Hot Springs Cove near Tofino, BC also applied for help in developing their hot springs for heating or other purposes. The cancellation of the National Geothermal Energy Program effectively halted these projects among others (Jessop, 2008a).

2.6.2 British Columbia

Due to its geologic conditions, British Columbia contains the vast majority of Canada's geothermal resources. Geothermal rights on Crown land have been granted on a small number of properties. To date, rights have been issued for the following locations in British Columbia: Mount Cayley, Canoe Reach/Valemount, South Meager/Pebble Creek, and Knight Inlet/Mount Silverthrone. Exploration at these sites is largely preliminary (i.e. geophysical surveys and minor amounts of drilling) and the sites have languished for various reasons, primarily economic and political.

A 2002 report by BC Hydro identifies 16 prospective geothermal sites in BC – the 6 sites with the highest potential for commercial development totaling 1070 MW (Table 2). The estimated levelized energy production cost for geothermal power is 5-9 cents/kWh (BC Hydro, 2002).

Table 2: BC geothermal potential modified from BC Hydro, 2002 report on green energy alternatives

Site Name	Location	Potential	Size
Meager Creek	Pemberton	Leased, possible commercial development	100-200
Pebble Creek	Pemberton	Very good	200
Lakelse	Terrace	Promising for binary plant	50
Mount Cayley	Squamish	Promising, but severe terrain	100
Mount Edziza	Telegraph Creek	Prospective, but little information available	200-500
Lillooet Fault Zone	Lillooet	Prospective, but little information available	20

The most advanced-stage geothermal prospect in Canada is at Mount Meager located at the intersection of the Garibaldi and Pemberton volcanic complexes 170 km north of Vancouver. Work at Mount Meager began in the late 1970s under the direction of BC Hydro; geothermal rights were later transferred to private interests in the 1990s. Exploration at Mount Meager has included drilling 19 holes, 3 of which were production-sized wells (Western GeoPower Corp., 2009). Deep drilling has confirmed resource temperatures as high as 270^{o}C at depths of ~3 km (Ghomshei, et al., 2004). The wells drilled to date have encountered relatively low permeability suggesting limited production of geothermal fluids. Valuable geologic information was obtained during drilling, and a zone of higher permeability has been identified with simulations indicating that wells targeting this area can produce about 6 MW each (Western GeoPower

Corp., 2009). The South Meager project is located on the traditional territory of the Lil'wat First Nations and is approximately 80 km from the grid (Western GeoPower Corp., 2009). A landslide at the site in August 2010 will likely hinder future development (Canadian Press, 2010).

Approximately 12 km from the Mount Meager project is the North Meager or 'Pebble Creek' prospect. Both locations are likely heated by the same source, however higher bottom hole temperatures at shallow depth (Nevin, 1992) and easier access led BC Hydro to focus instead on South Meager. Nine slim-holes at Pebble Creek showed linear temperature gradients of ~90^{o}C/km, with the highest reported gradient of 210^{o}C/km. After encountering low permeability in drilling at the South Meager project, it is now thought that the lithology at the North Meager/Pebble Creek prospect may have a greater chance of adequate permeability (Nevin, 1992). Many studies have been done since 1992 that may support or counter this statement, but unfortunately this work is proprietary.

Mount Cayley was the first private geothermal lease granted in Canada under the B.C Geothermal Act of 1983. Following preliminary exploration work by the Geological Survey of Canada, O'Brien Resources was awarded the geothermal rights for Mount Cayley (O'Brien Energy & Resource Limited, 1984). Geothermal exploration work included drilling of 5 slim holes that intersected gradients of 50 to 100^{o}C/km (Nevin Sadlier-Brown Goodbrand, 1982). BC Hydro conducted geochemical sampling from hot springs and creeks that showed indications of complex mixing and dilution of geothermal waters rendering geothermometry estimates of reservoir temperature unreliable (Nevin Sadlier-Brown Goodbrand, 1983). Geophysical surveys of the Mount Cayley area including direct current and dipole-dipole resistivity surveys have defined several conductive zones associated with the thermal anomaly (Souther & Dellechaie, 1984). A total of 10 whole rock K-Ar samples were tested to determine the age of rocks at Mount Cayley, which ranged from about 0.2 to 5.7 million years (Souther & Dellechaie, 1984). The evidence of young silicic volcanism supported by the fact that Mount Cayley lies within the same volcanic complex as Mount Meager (temperatures >200 ^{o}C) indicate geothermal potential (O'Brien Energy & Resource Limited, 1984). The heat source has yet to be confirmed through deep drilling, however seismic reflection investigations (for non-geothermal purposes) have identified a mid-crustal reflector about 12-13 km below Mount Cayley which may be related to a magma chamber or melt lens beneath the volcanic edifice (Hammer & Clowes, 1996).

Another lease area is the Canoe Reach hot springs located about 35 km from Valemount in western BC. Hot Springs at the site show surface temperatures of 70 to 80^{o}C and geothermometry estimates are 125^{o}C (silica) and 180^{o}C (cation) (Ghomshei, Kimball, & Porkial, 2009). There is no direct evidence of recent volcanism in the area, and a plausible heat source is deep-seated faults in the Southern Rocky Mountain Trench. A recent magneto-telluric survey flown over the hot springs area revealed a low resistivity anomaly associated with the known hot springs as well as an additional area across the Canoe River that may also be prospective for geothermal energy (Ghomshei, Kimball, & Porkial, 2009).

3 Geographic Information Systems

Geographic Information Systems (GIS) are based on the underlying principle that spatial location is important in data analysis. The main functions of a GIS are: mapping, measurement, monitoring, modeling, and management of data (Longley, Goodchild, Maguire, & Rhind, 2005). There are several examples of the successful application of GIS to the geothermal sector either for management of geothermal-relevant data and/or spatial modeling.

3.1 Database Management

As Einarsson & Hauksdottir (2010) recognize, geothermal data exists in all resolutions and in all dimensions, but with a common feature of having a spatial component. The management of geothermal data is therefore important at different stages of a geothermal project from regional exploration, local exploration, development, and production.

Examples of geothermal GIS for data management are available from Germany (Pester, et al., 2010), Korea (Kim, Baek, & Park, 2010), Switzerland (Kohl, Signorelli, Engelhardt, Andenmatten Berthoud, Sellami, & Rybach, 2005), and Turkey (Basel, Satman, & Serpen, 2010). These tools are largely used for data management and visualization with modeling and analysis left to the user.

Vector data typically comprises discrete objects (e.g. well locations, hot springs) represented as points, polylines, and polygons and is more precise than raster data. Raster data comprises fields and involves dividing data into an array of cells where each cell is assigned an attribute. Details about variation within a cell are lost during the rasterization process however the method does facilitate the use of mathematical operations for analysis.

A common GIS transformation is spatial interpolation that allows the user to estimate the value of a property at an un-sampled site within an area covered by existing observations. After spatial interpolation, spatial modeling can be performed with the GIS. These methods have been used to generate heat flow maps and/or temperature gradient maps in many regions, including the United States (Tester, et al., 2006), Canada (Grasby, Majorowicz, & Ko, Geothermal Maps of Canada, 2009), Turkey (Basel, Satman, & Serpen, 2010), and the Fort Nelson area in northeast British Columbia (Arianpoo, 2009).

3.2 Modeling

Spatial modeling allows the user to simulate real world processes. For example, GIS models can be used to determine the most suitable site to drill a geothermal well - a technique used at the Sabalan geothermal field in Iran (Noorollahi, Itoi, Fujii, & Tanaka, 2008) and at the Los Azufres geothermal field in Mexico (Prol-Ledesma, 2000). Noorollahi et al., (2008) successfully integrated an index overlay model of geothermal resource factors with an environmental suitability model to select the location for 3 exploratory wells at the Sabalan geothermal field (now producing 55 MWe). Resource suitability areas were scored from 1 to 9 based on the integration of geological, geochemical, and geophysical data sets. Environmental suitability was determined from slope, vegetation, land use, surface drainage, and residential areas. Targets were selected from areas with the highest resource suitability scores that also intersected with environmentally suitable areas.

GIS-based models have been used to predict where a mineral resource is likely to occur, or similarly where favourable locations for geothermal exploration exist. Geothermal predictive and favourability mapping has been undertaken in Nevada, (Coolbaugh, 2002), and later extended to the Great Basin, (Coolbaugh, 2005). Other regional studies include Akita and Iwate Prefectures in northern Japan (Noorollahi, Itoi, Fujii, & Tanaka, 2007), West Java in Indonesia (Carranza, Wibowo, Barritt, & Sumintadireja, 2008), Iran (Yousefi, Ehara, & Noorollhai, 2007), (Yousefi, et al., 2010), and the Northwest Territories in Canada (EBA Engineering Consultants Ltd., 2010).

GIS models are either data-driven or knowledge-driven; however both employ a conceptual model of resource potential that provides knowledge of spatial associations between the potential resource and evidence (i.e. geologic features) of the resource. Data-driven models process the input data using weights of evidence, logistic regression or neural network analysis. They require training data (e.g. geothermal production sites) to calculate model parameters. Knowledge-driven models include model parameters that are estimated by an expert using fuzzy data analysis or Bayesian probability (Bonham-Carter, 1994; Bonham-Carter et al., 1994). The geothermal examples studied used one or more of the above methods, depending on the availability of training sites, software, and other factors.

Input data for existing geothermal favourability maps includes geologic features (faults, volcanic centers, volcanic rocks), geochemical features (hydrothermal alteration, fumaroles, hot springs, geothermometry), thermal features (geothermal gradient, heat flow), and geophysical features (gravity, resistivity, and magnetics). If there are known geothermal occurrences, they can also be incorporated into data-driven models to statistically quantify the relationship between the input data and favourable areas predicted by the model.

The favourability map of Nevada (Coolbaugh, et al., 2002) uses weights of evidence analysis to determine the correlation between evidence layers and training sites; logistic regression methods are used to integrate the evidence layers and their assigned weights into a predictive model to locate geothermal systems. The Great Basin geothermal favourability map (Coolbaugh, et al., 2003), (Coolbaugh, Zehner, Kreemer, Blackwell, & Oppliger, 2005) uses weights of evidence and logistic regression methods and compares the outcome with Bayesian probability methods (Coolbaugh & Bedell, 2006).

For favourability mapping in Japan and Iran, a model called the GIS Model for Geothermal Resource Exploration (GM-GRE) was used to build favourability maps. Spatial distribution analysis was performed to determine the relationship between existing geothermal wells and various evidence layers. The three layers containing geological, geochemical, and thermal evidence were assigned different weights based on importance which were combined in a type of multi-criteria evaluation (MCE). For the map of Iran, a Boolean logic model was used to integrate evidence contained in factor maps into suitability maps for geological, geochemical and geophysical evidence.

A predictive map for the island of West Java, Indonesia compares data-driven and knowledge-driven models for regional-scale geothermal exploration. This work included a spatial distribution analysis followed by a spatial association analysis (after Bonham-Carter, 1994) to develop spatial recognition criteria of regional-scale geothermal potential. The analysis yielded information on the most useful indicators and their distance of influence. In the data-driven model, evidential belief functions (EBFs) were applied and evidential maps comprising the integrated EBFs were generated. Using the Dempster-Shafer theory of evidence, 2 evidential maps were combined using AND/OR operations allowing for logical and systematic application of the conceptual model. For example, integrated EBFs of “geothermal circulation” AND integrated EBFs of “cap/reservoir rocks” were combined to produce an integrated EBF of “regional-scale geothermal potential” (Carranza, Wibowo, Barritt, & Sumintadireja, 2008).

3.3 Methodology in this Research

A total of 10 evidence layers were compiled using publicly available data sets for the province of British Columbia. Raw data was transformed into a standard raster grid covering the entire province with a cell size of 1 km X 1 km, enabling comparison of different attributes from each layer using a common geometric base. Input data was re-classified and assigned a score from 1-5 to allow normalized comparison between the data sets; in cells with no data, a score of 0 was assigned.

The 10 evidence layers are grouped into 5 factor maps:

1. Temperature
2. Permeability
3. Resource (a combination of 1 and 2)
4. Market and Infrastructure
5. Land Use

The final geothermal favourability map of British Columbia is a combination of factor maps 3 and 4 and highlights the areas within the province that are most prospective for geothermal given the existing data. The map can also be modified with the 5th factor map to accommodate areas not eligible for geothermal tenure. The above maps are created and combined using a knowledge-driven model involving multi-criteria evaluation described in Chapter 6. The lack of training sites or known geothermal occurrences in British Columbia (with the exception of Mount Meager) precludes use of data-driven statistical methods for the BC map. Environmental Systems Research Institute's ArcGIS version 9.3.1 is used for the favourability mapping presented here. Alternative software such as IDRISI is also available from Clark Labs.

3.4 Sources of Data

The main sources of data for the province were the British Columbia Ministry of Energy Mines and Petroleum Resource (BC MEMPR) and the British Columbia Geological Survey (BCGS). Data is compiled by BC MEMPR through an Internet based viewing platform (www.mapplace.ca). The over 30 thematic maps and the ancillary geospatial data available from BC MEMPR were reviewed to assess their application for geothermal. The most pertinent map was the Geothermal Resource of British Columbia map (Fairbank & Faulkner, 1992) comprising vector data on geology, hot springs, boreholes, heat generation, and geothermal potential. The 1992 map (Figure 3) is a major data source for the favourability map and the interpretation of geothermal potential in this map is used for comparison.

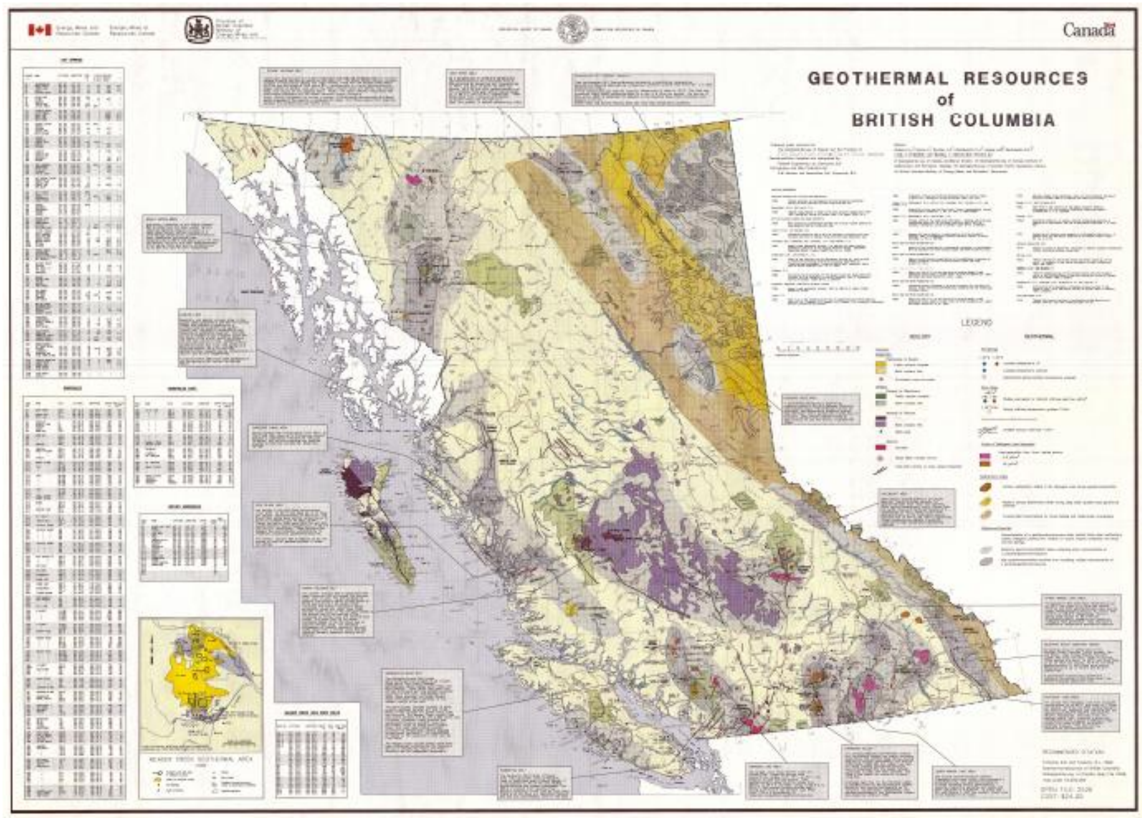

Figure 3: Map of geothermal resources of British Columbia (Fairbank & Faulkner, 1992)

4 Resource

The quality of a geothermal resource is a function of its temperature and permeability. In the favourability analysis of British Columbia, 5 evidence layers are used as indicators of elevated temperatures (Figure 4).

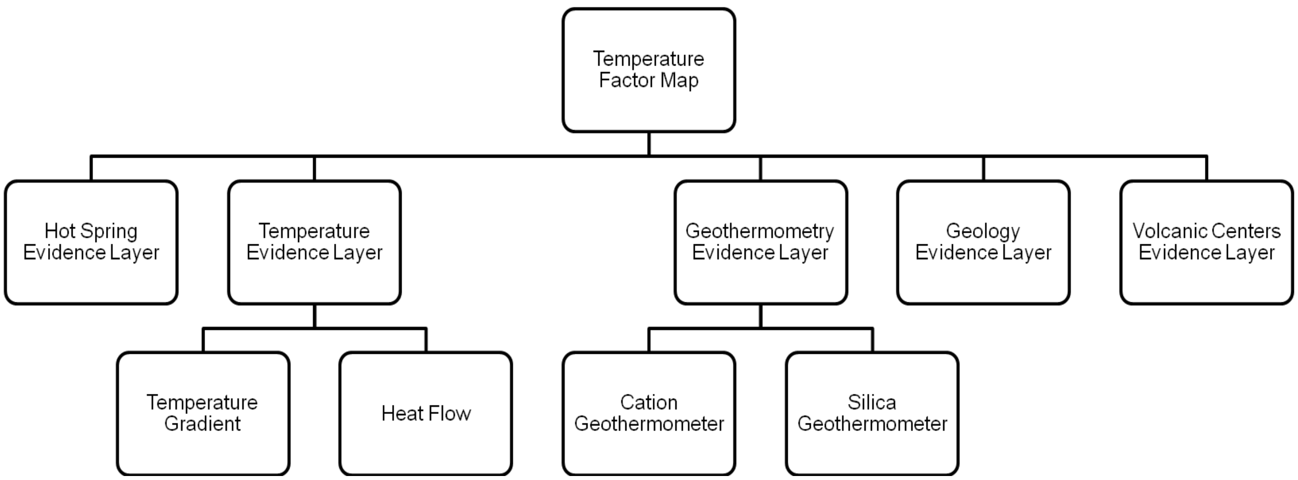

Figure 4: Heat indicators and evidence layers used in the temperature factor map

The permeability of a geothermal system is the path through which hot geothermal fluids travel. In the permeability factor map, two indicators are used (see Figure 5).

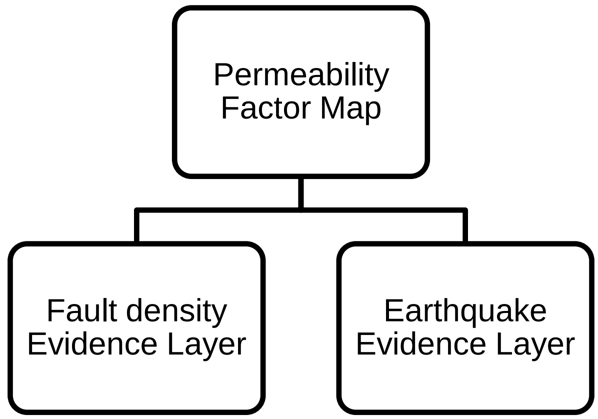

Figure 5: Evidence layers in the permeability factor map

4.1 Temperature Factor Map

4.1.1 Temperature Gradient

The most important and unambiguous feature for geothermal energy exploration is the local temperature gradient at a site. The average crustal temperature gradient is 20 to 30^{o}C/km (Winter, 2008); however geothermal resources are located in areas with elevated gradients, often as high as 100^{o}C/km. The Great Basin favourability map includes shallow (0-1km) temperature gradient maps derived from interpolation of heat flow data and conversion to temperature gradient using thermal conductivities assigned for grouped geologic formations (Coolbaugh, Zehner, Kreemer, Blackwell, & Oppliger, 2005). For the favourability map in northern Japan, temperature gradients were classified into 5 groups and given a weight between 0 and 1 (Noorollahi, Itoi, Fujii, & Tanaka, 2007), see Table 3.

Table 3: Temperature gradient classification for northern Japan, from Noorollahi (2007)

Temperature Gradient (^{o}C/km)	Weight
<30	0.1
31-50	0.3
51-100	0.5
101-200	0.8
>200	0.9

Temperature gradient is calculated from measurement of absolute temperature at corresponding depths from boreholes. Corrections for certain drilling and geologic factors can be applied to the temperature values if necessary.

Equation 1: Temperature gradient

$$\nabla T = \frac{T_2 - T_1}{D_{2-}D_1}$$

The primary source of temperature data for the BC map was the Canadian Geothermal Data Compilation (Jessop, et al., 2005). Sites in databases within BC were identified and the logs were plotted (for example, Figure 6: Temperature gradient plot for Penticton), and inspected to see if corrections were required. If there were multiple logs from a site, the gradient of each log was calculated and averaged with other logs from the site to provide a single data point for the site.

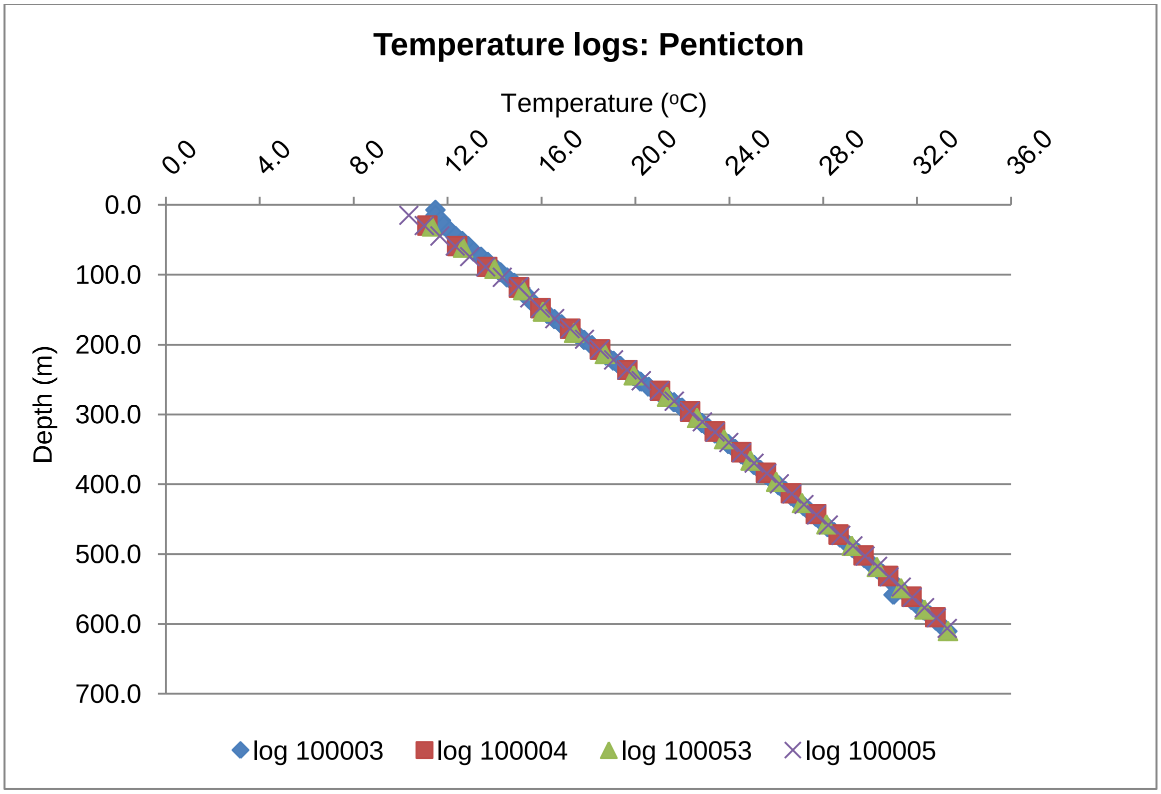

Figure 6: Temperature gradient plot for Penticton

It was assumed that sufficient time after drilling had passed for the well to equilibrate so no drilling correction method was required. Corrections for inclination were applied by using the vertical depth in those cases where the borehole was drilled at an angle. Corrections for climatic variations were made by eliminating the shallow portion of wells that were clearly affected by seasonal variations. In some cases, this resulted in discarding entire logs that were too shallow. Similarly, at sites with multiple logs reaching different depths, deeper logs were considered more reliable. Furthermore, portions of the log that appears to be affected by water flow in or out of the borehole or topography effects (e.g. Squamish Valley, Liilooet Valley, Upper Liilooet River, and Mount

Meager) was not included in the database as the data was considered to be un-representative (see Figure 7). Calculated temperature gradients from the Canadian Geothermal Data Compilation are included in Appendix A.

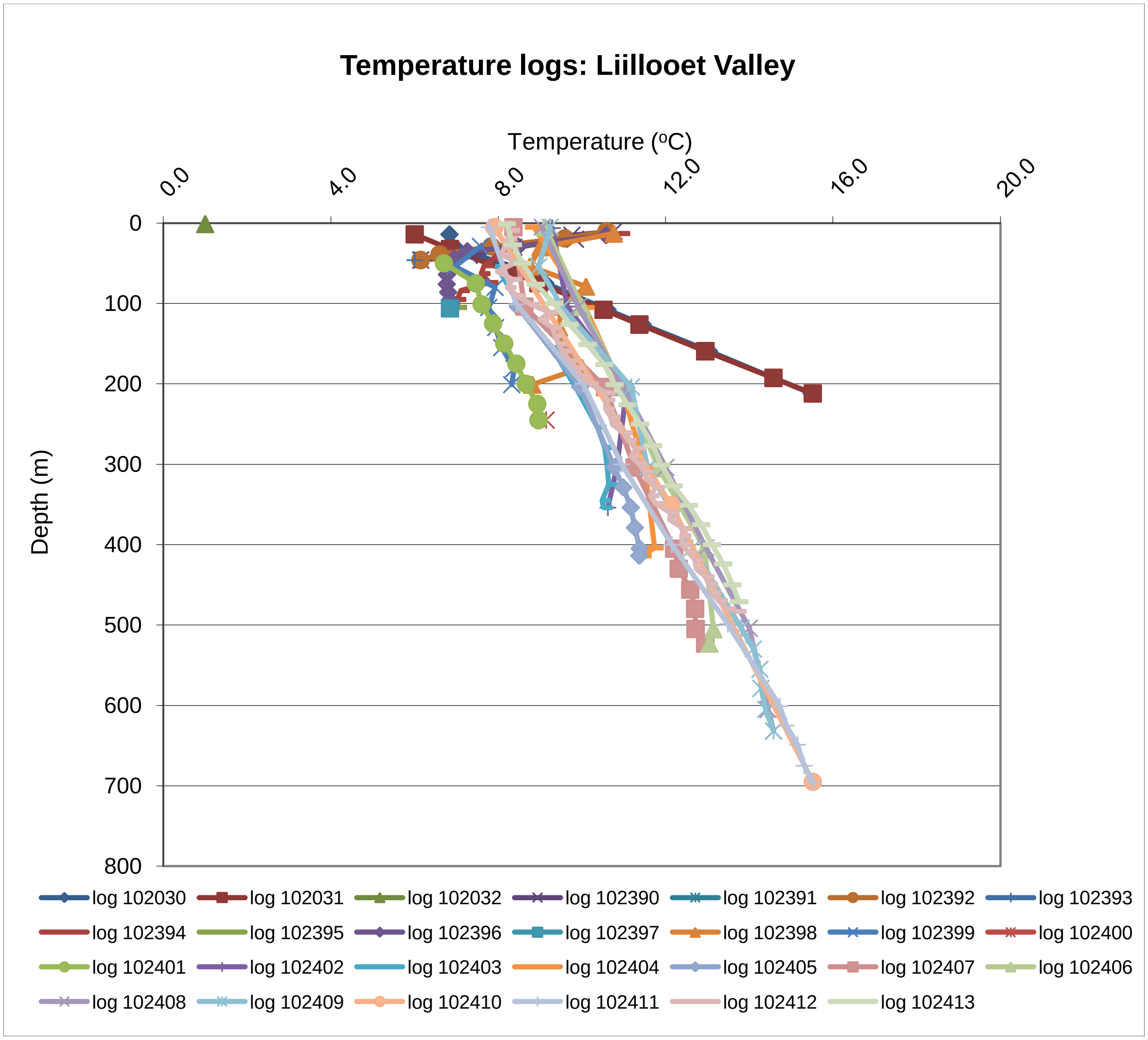

Figure 7: Temperature gradient plot for Liilooet Valley showing multiple logs with generally poor agreement likely due to topographic and hydrology effects in the shallow subsurface.

In addition to the gradients calculated from the Canadian Geothermal Data Compilation, published temperature gradient values for Mount Meager: 150°C/km from Ghomshei et al, (2004), and data from the Global Database of Borehole Temperatures and Climate Reconstructions[4] (Huang, Pollack, & Shen, 2000) was also included.

The temperature gradient data points (Figure 8) were converted to a raster with cells within a 25 km radius assigned a score from 1-5 based on the temperature gradient value. The temperature gradient classes used for assigning the score are based on the required temperature for commercial geothermal power generation of 150°C, and a drillable depth limit of 5 km. A minimum temperature gradient of 30°C/km is required, thus all temperature gradients below 30°C/km are considered low and assigned a score of 1(Figure 9).

A higher gradient reduces the drilling depth and enhances the economics of the project, reflected in the higher scores assigned to gradients above 30°C/km. When compared to temperature gradients and scoring in Japan (Table 3), the BC scoring assigns higher values to lower temperature gradients. This is due to the inherent higher temperature gradients found in the Japan study area compared to British Columbia.

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[4] Available at http://www.geo.lsa.umich.edu/clihttp://www.geo.lsa.umich.edu/climate/NAM.html

Table 4: Scoring table for the temperature gradient evidence layer

Score	Temperature Gradient (^{o}C/km)
0	No data
1	<30
2	30-40
3	40-50
4	50-60
5	>60

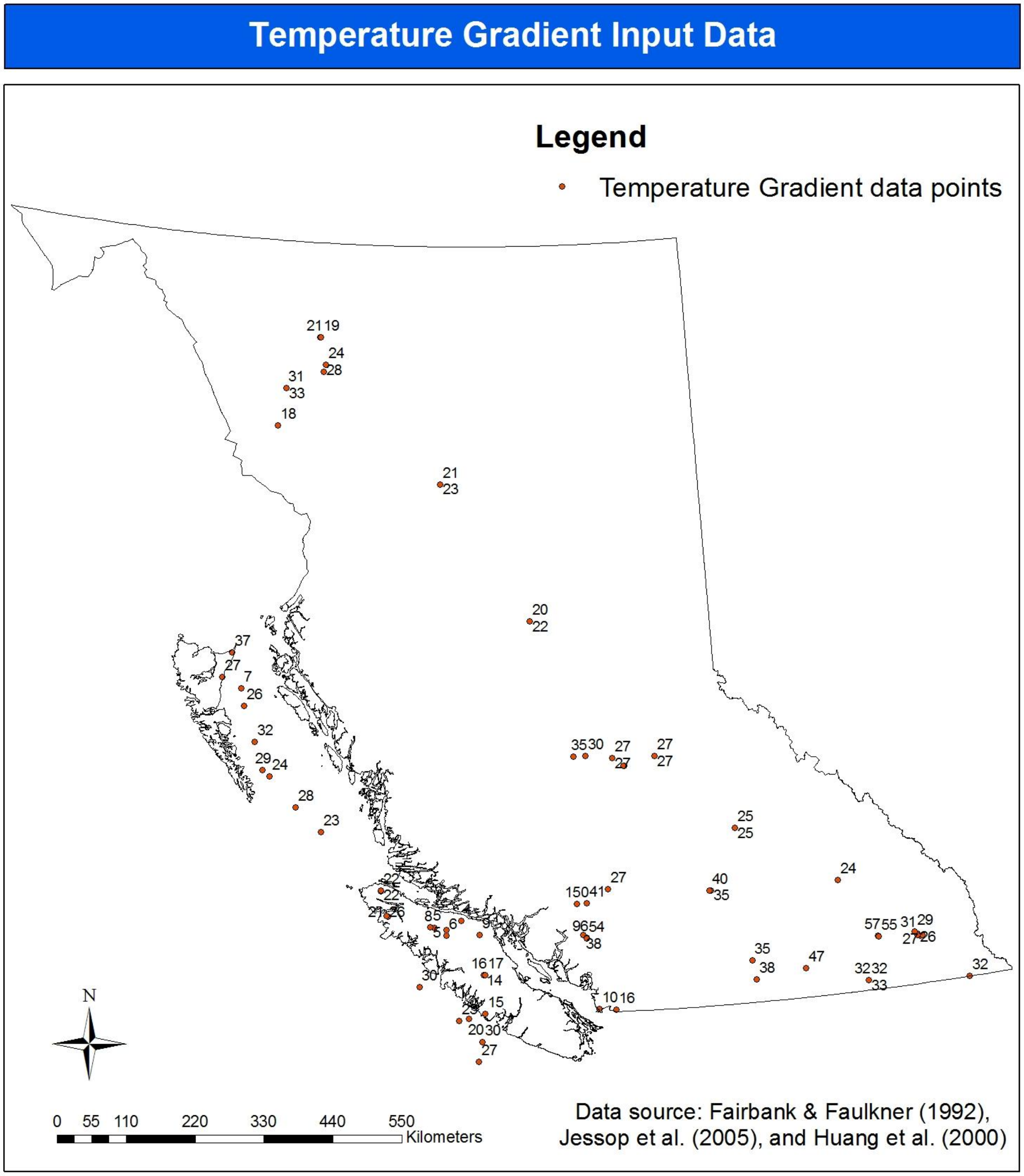

Figure 8: Input data for the temperature gradient evidence layer

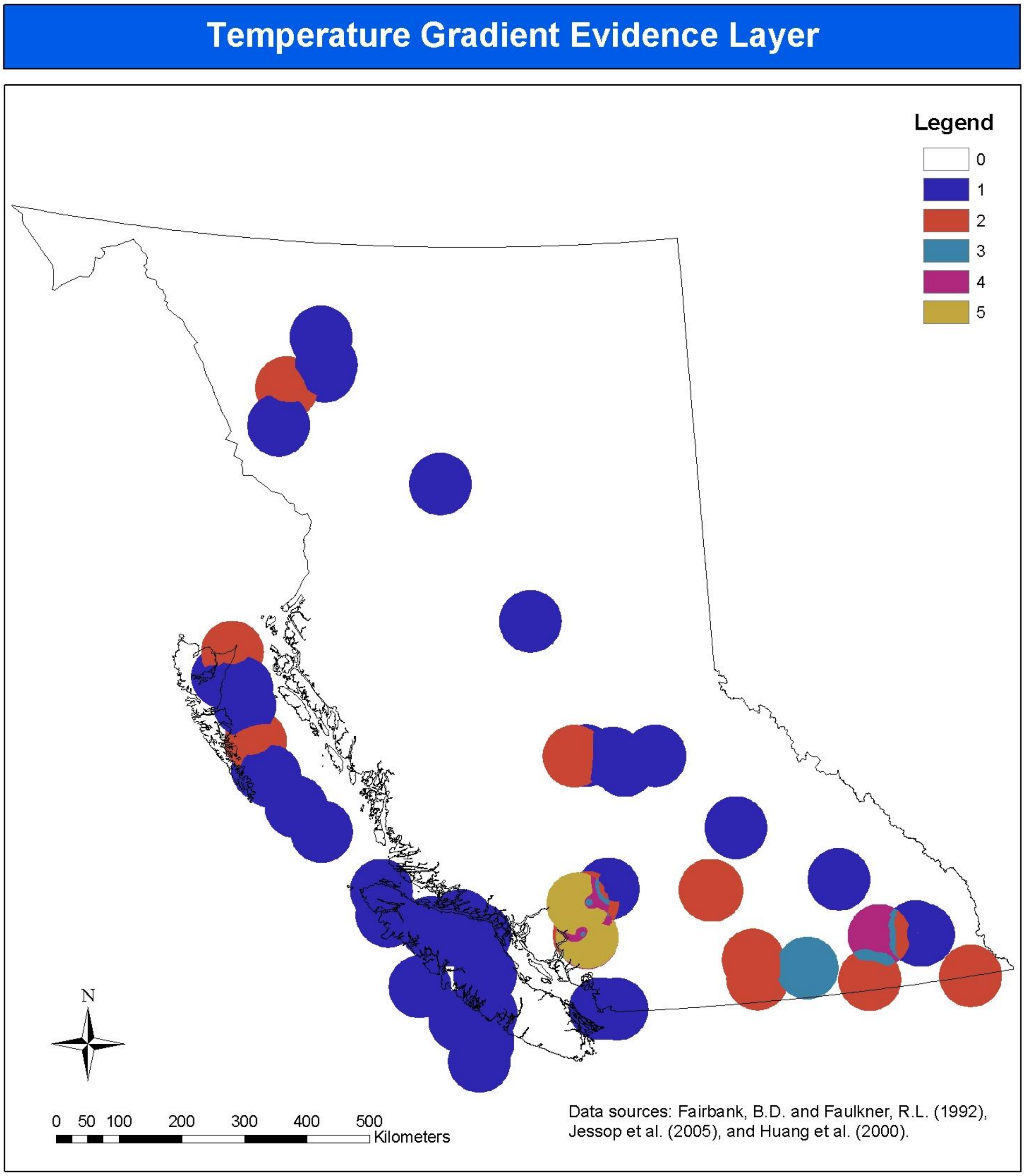

Figure 9: Output raster for the temperature gradient evidence layer

4.1.2 Heat Flow

Areas of elevated heat flow are favourable for geothermal exploration. Heat flow and temperature gradient are related through Fourier's Law of Conduction which states that heat flow (Q) is equal to the product of thermal conductivity (K) and the temperature gradient.

Equation 2: Heat Flow $Q = K * \nabla T$

Data related to temperature gradients is often reported as heat flow since this value does not change with depth. Surface heat flow has two components: heat flow from the mantle and heat generation from radioactive elements U, Th, and K found in the crust. Mantle heat flow which is typically associated with plate tectonic activity, young volcanism, and intrusions has the greatest effect on overall heat flow.

Two types of heat flow data were used in the favourability analysis: individual borehole data (points) to capture local heat flow variations and a heat flow map (polygons) to capture regional heat flow variations. Individual borehole data for heat flow was obtained from Fairbank & Faulkner (1992), and the International Heat Flow Commission (International Heat Flow Commission, 2010). Borehole data from all sources were combined and duplicates removed (Figure 10). A buffer of 25 km around each borehole was assigned.

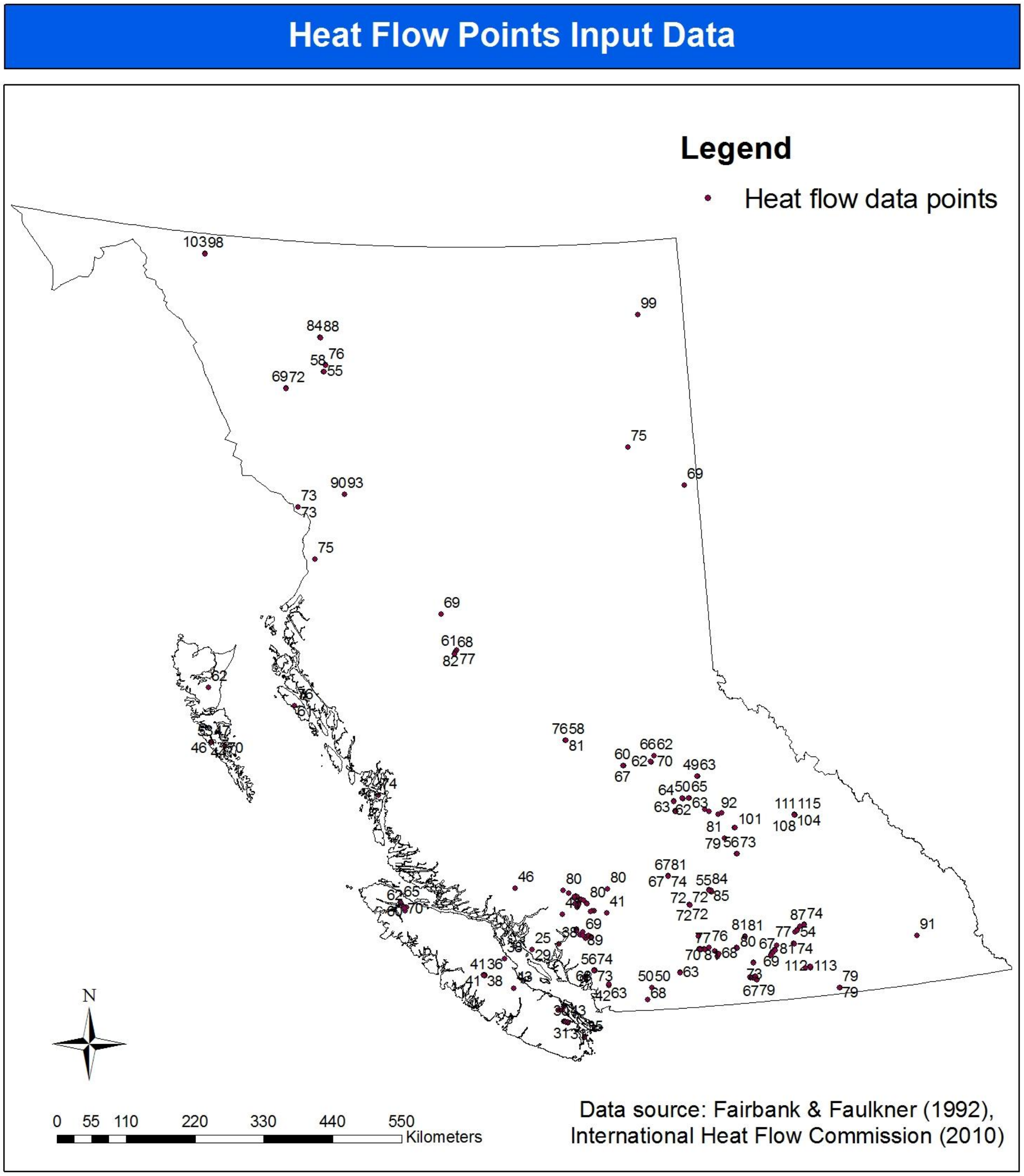

Figure 10: Heat flow input data from borehole measurements

A heat flow map of BC was digitized from geothermal maps of Canada by Grasby, Majorowicz, & Ko, 2009 (Figure 11) and heat flow regions were converted to a raster.

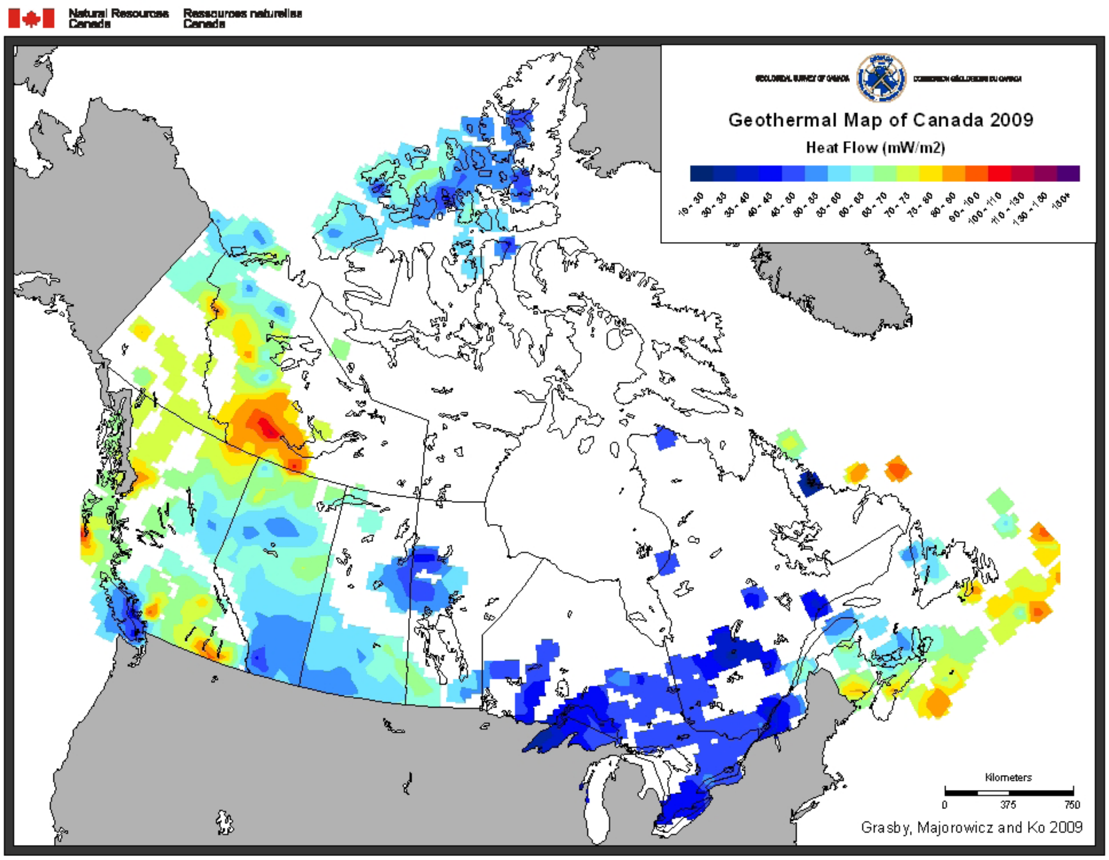

Figure 11: Heat flow map of Canada digitized in GIS for the favourability analysis

Both the local and regional rasters were re-classified using the same scoring table based on the heat flow value of the feature (Table 5). The World average heat flow is approximately 80 mW/m^2 (Condie, 1997), and heat flow values below the world average are assigned a score of 1, while higher heat flow values are assigned scores as high as 5. The local and regional heat flow rasters were combined with the maximum score in each cell comprising the final raster (Figure 12).

Table 5: Scoring table for the heat flow evidence layer

Score	Heat Flow (mW/m^2)
0	No data
1	<80
2	80-90
3	90-100
4	100-110
5	>110

In order to avoid redundancy and “double counting” of heat flow and temperature gradient, the final heat flow raster and final temperature gradient raster were combined using the maximum score value of each cell to create a Temperature Evidence Layer (Figure 13).

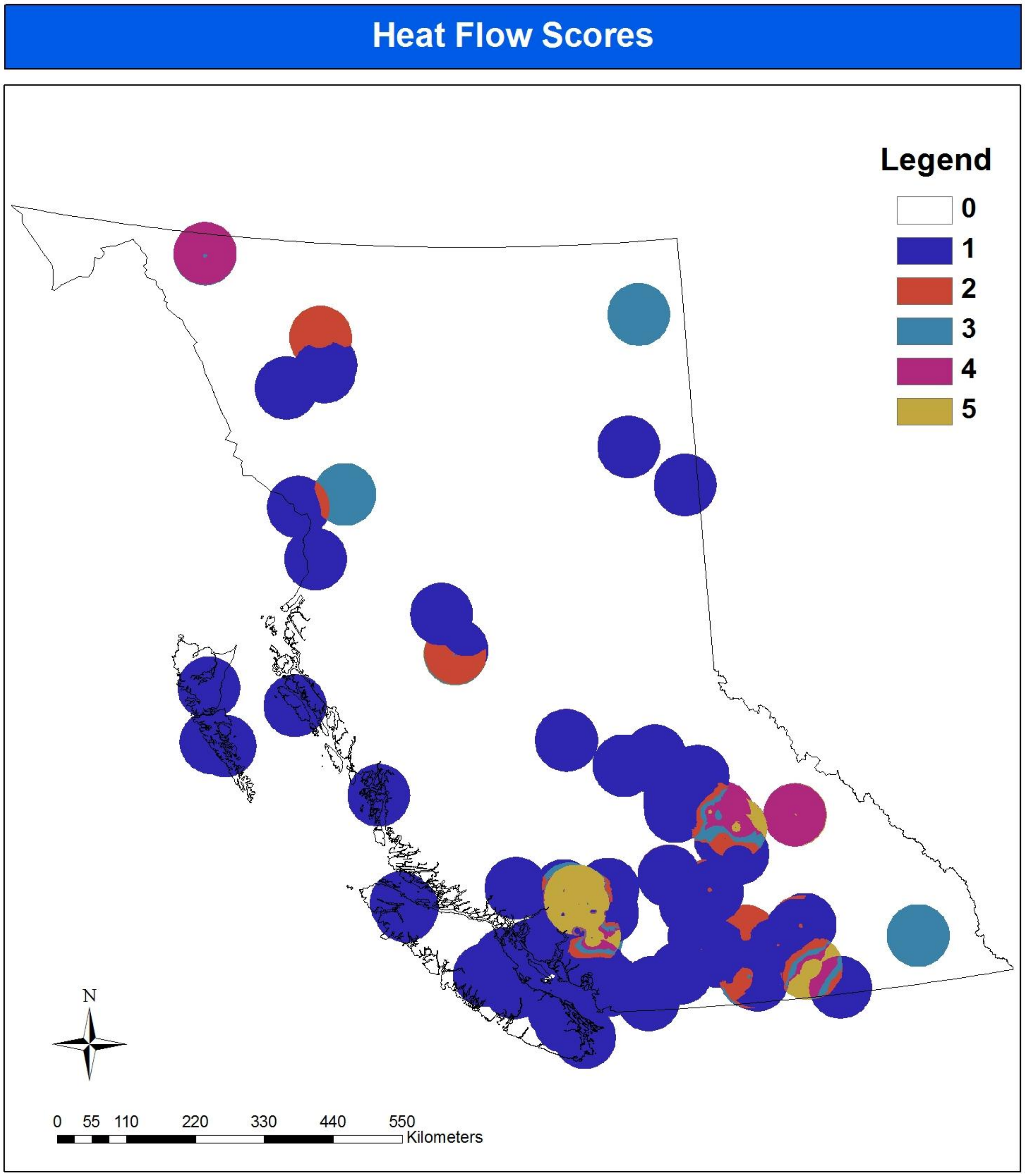

Figure 12: Output of heat flow borehole data

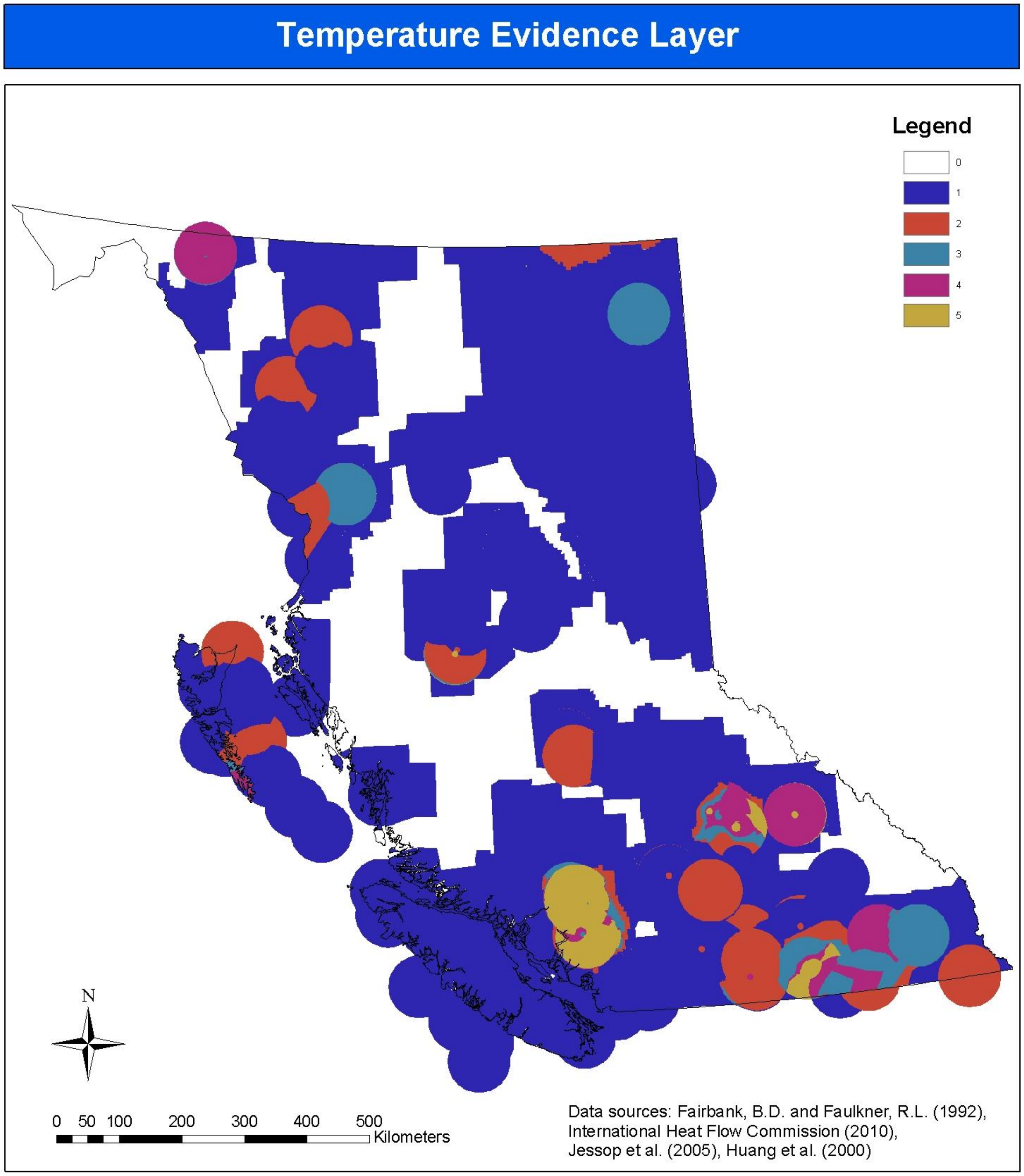

Figure 13: Temperature evidence layer using the maximum score of the temperature gradient/heat flow layers

4.1.3 Hot Springs

The presence of hot springs has led to the identification of several geothermal resources in the world (e.g. Taupo, New Zealand; Iceland, etc.) A spring hotter than the ambient air temperature (usually 5^{o}C depending on the climate) is of interest to the geothermal explorer. In Canada, previous studies (e.g. Grasby & Hutcheon, 2001 and Fairbank & Faulkner, 1992) have adopted a threshold of 10^{o}C for springs to be considered hot and the same threshold is used in the present work.

In western Canada, three main types of hot springs are identifiable by their chemical composition and geologic setting: (1) springs associated with deep flow systems 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 (Jessop, 2008b and Woodsworth, 1997). In British Columbia, (Grasby & Hutcheon, 2001) have shown that the distribution of thermal springs is largely controlled by faults (particularly in the Southern Rocky Mountain Trench), and to a lesser degree, by the presence of volcanoes.

Descriptions, temperature data, and locations of hot springs of western Canada are documented in different guidebooks primarily used for tourism (Woodsworth, 1997); (McDonald,1991). The geothermal resources map of BC (Fairbank & Faulkner, 1992) shows 107 springs in BC with Lakelse hot spring having the highest temperature at 86^{o}C. Hot Springs input data is shown in Figure 14.

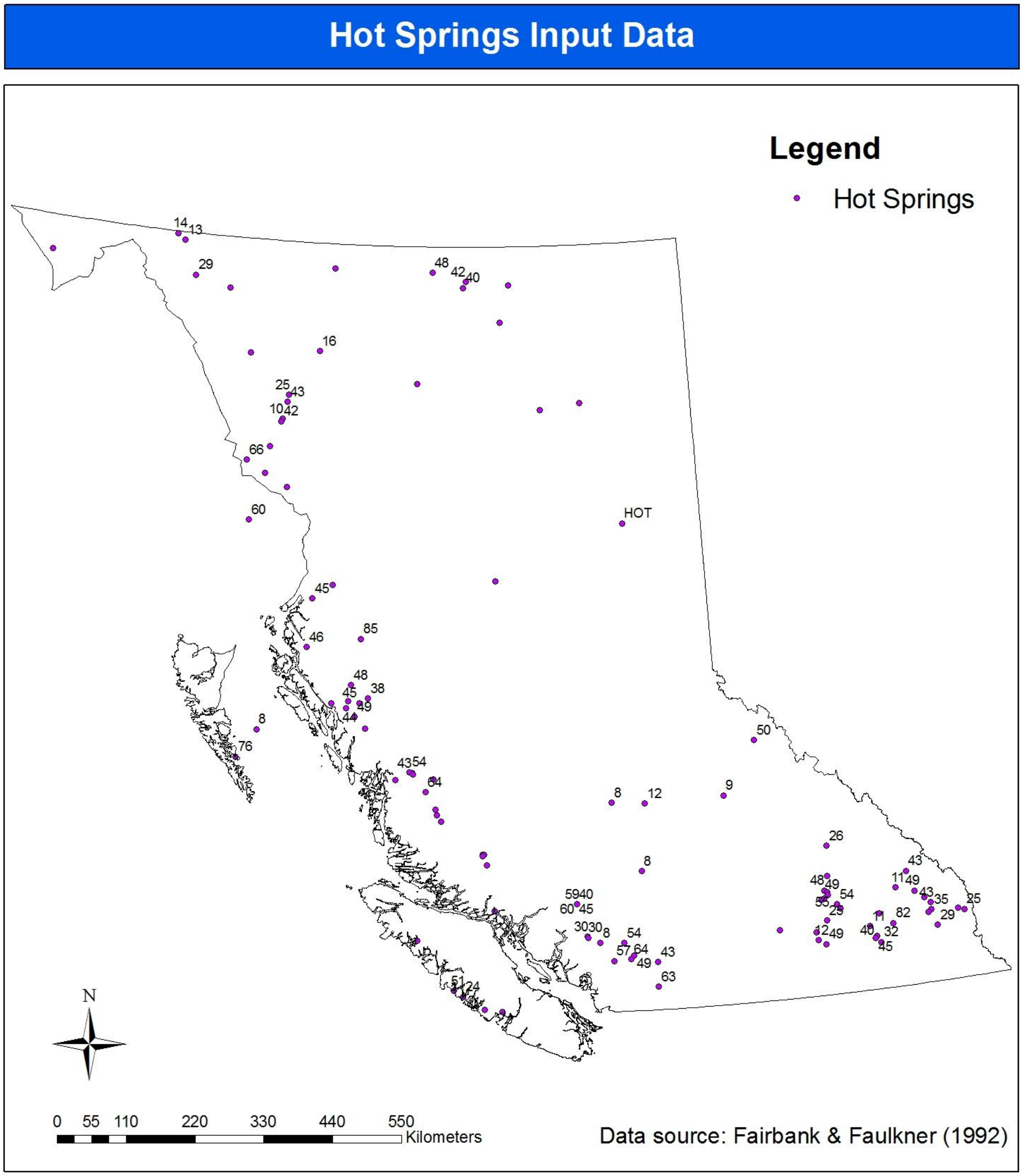

Figure 14: Input data for the hot springs evidence layer

For the favourability analysis, cells within a 4 km radius (the same distance used by Yousefi, et al., 2010 for hot springs in Iran) of a hot spring were assigned a score from 1-5 based on the temperature of the hot spring (Table 6).

Two hot springs included in the dataset did not have numerical values, but included linguistic terms from which a judgment was made to assign them a score. The resulting Hot Springs Evidence Layer is shown in Figure 15.

Table 6: Hot springs scoring table

Score	Hot Springs Temperature (^{o}C)
0	No data
1	<20
2	20-40/"WARM"
3	40-60/”HOT”
4	60-80
5	>80

It is important to note, that the absence of thermal springs in a region is not indicative of geothermal potential, and that low-temperature discharge can be associated with either low or high temperatures at depth (Ferguson, Grasby, & Hindle, 2009). Nevertheless, hot springs do provide a surface indication of anomalous heat flow that may be linked to a high-temperature geothermal system at depth and hot springs are commonly used in geothermal exploration.

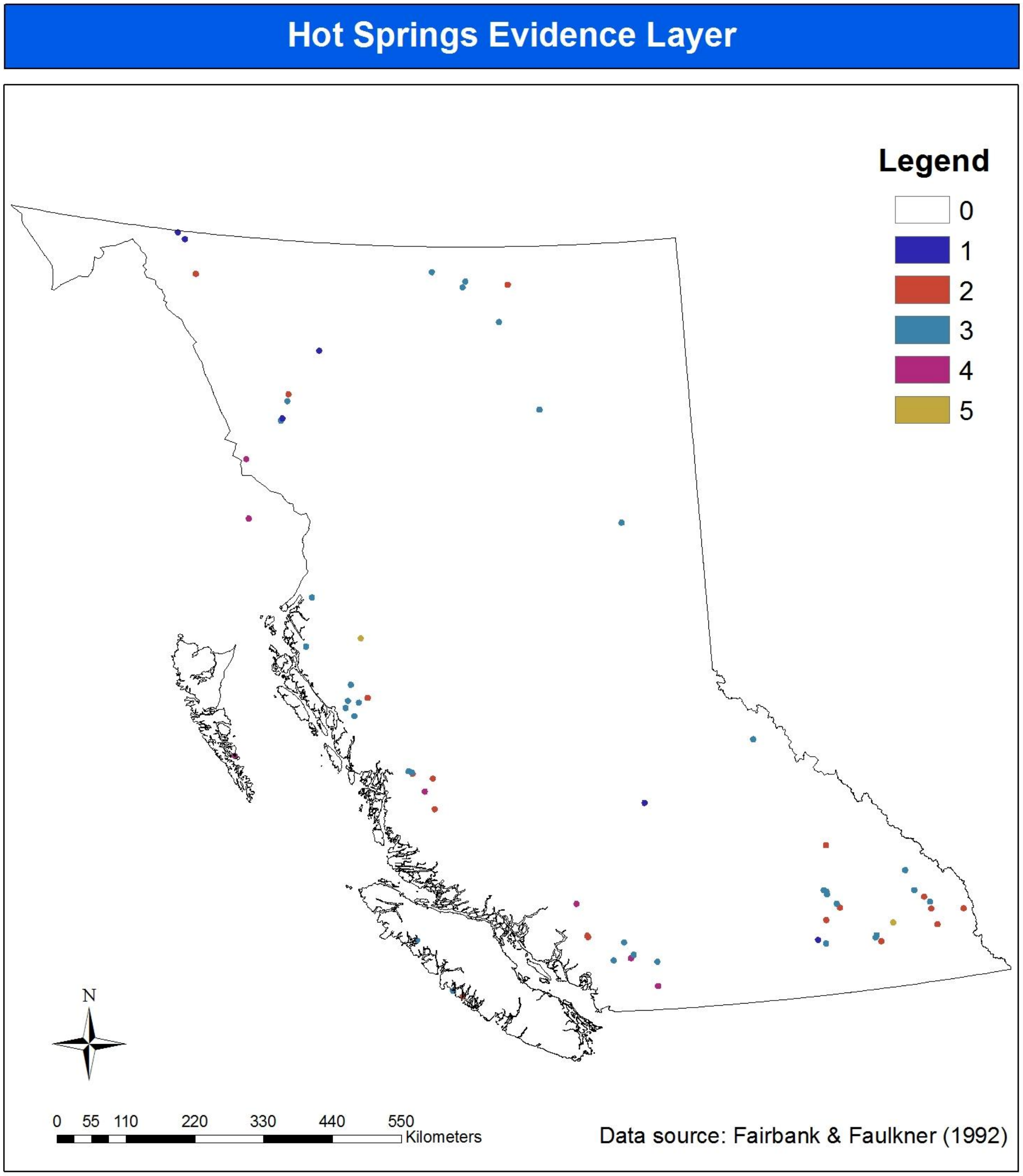

Figure 15: Hot springs evidence layer

4.1.4 Geothermometry

The chemistry of spring waters can be used to estimate the equilibrium temperature of water-rock interaction, which is a proxy for the resource temperature of a geothermal system. Several empirically-derived geothermometer equations are available, but the most commonly applied equations rely on the concentration of cations (Na, Ca, K, Mg, etc), and of silica (SiO_2) to predict the subsurface temperature.

Waters may be affected by surficial processes namely, mixing, re-equilibration, evaporation, and other water-rock interactions while ascending to the surface. These processes, will affect the outcome of the geothermometry calculations. For example, cation geothermometers (that include Ca concentrations) are unreliable if the waters have travelled through thick sequences of carbonate rocks (Crandall & Sadlier-Brown, 1978).

Regional and focused geochemical surveys are available from the BC Government on Map Place. These surveys cover approximately 75% of the province and include nearly 60,000 stream sediment and water samples. Unfortunately, this geochemistry data has limited utility for regional geothermal exploration since they are not sampled directly from hot springs and are mixed with surface and meteoric waters.

Geochemistry data suitable for geothermal exploration is available through published reports on geothermal exploration, (Nevin Sadlier-Brown Goodbrand, 1983); (Nevin, Sadlier-Brown Goodbrand Ltd., 1974); (Fairbank & Faulkner, 1992); academic literature (Grasby & Hutcheon, 2001) (Ghomshei, Kimball, & Porkial, 2009); (Allen, Grasby, & Voormiej, 2006) (van Everdigen, 1972) and presentations (Franz, 2010).

Data from these sources was entered into the liquid analysis spreadsheet from Powell & Cumming (2010) to confirm geothermometry calculations from the publications and ensure the most widely-used and relevant geothermometers equations were used. Raw data for springs from Fairbank & Faulkner (1992) and Franz (2010) was not available, so published geothermometer values were not confirmed with the Powell & Cumming spreadsheet. Powell & Cumming (2010) calculates 10 different geothermometers, however only three geothermometers were considered as suitable for geologic conditions found in BC. Amorphous silica does not control the solubility of silica in BC, so the amorphous silica geothermometers is not used. Cation geothermometers requiring Mg values are not used because Mg data values are not always analyzed, or the required resolution for Mg (<0.1mg/L) was not met by the lab (Powell & Cumming, 2010). The Quartz geothermometer with maximum steam loss is not applicable to BC hot springs because no hot springs are found at boiling conditions. Finally, the Na-K geothermometers provide values that are unreasonably high (i.e. above 400^{o}C) and inaccurate (Allen, Grasby, & Voormiej, 2006). Geothermometer equations for Na-K-Ca has been found to be consistent with well temperatures (Powell & Cumming, 2010) and is used by other authors for BC hot springs (Allen, Grasby, & Voormiej, 2006) and (Fairbank & Faulkner, 1992).

Silica-based geothermometers have faster reaction rates and are influenced by mixing and dilution and are more likely to be representative of a shallow aquifer (Powell & Cumming, 2010). This often leads to lower temperature estimates for silica-based geothermometers (relative to cation geothermometers). Therefore the scoring classes for both geothermometers apply to different temperature ranges (Table 7).

The choice of which silica-based geothermometer to use depends on which mineral is controlling the solubility of silica in the waters. Chalcedony is often more appropriate for water from a lower temperature source, however in the absence of field observation of geologic conditions, it is difficult to know which equation should be used. For this work, the higher value of either the Chalcedony (Equation 3) or Quartz (Equation 4) geothermometers was used, unless otherwise specified by the original author (see Appendix B). The input data points for the silica geothermometer are shown in Figure 16.

Equation 3: Chalcedony geothermometer:

$$Chalcedony\ T(°C) = \left[\frac{1032}{(4.69 - logSiO_2)}\right] - 273$$

Equation 4: Quartz geothermometer:

$$Quartz, no\ steam\ loss\ T(°C) = \left[\frac{1309}{(5.19 - \log{(SiO_2)})}\right] - 273$$

Na-K-Ca cations have slower reaction rates than silica and thus provide estimates for the maximum temperature of the geothermal reservoir. The Na-K-

Ca geothermometer (Equation 5) is based on equilibrium constants between various feldspars, micas, zeolites, or clays under conditions of high temperature and pressure. In using concentration ratios, cation geothermometers are less sensitive to changes in the strength of the solution due either to boiling or dilution that silica geothermometers (Williams, Reed, & Mariner, 2008). Data points from the cation geothermometer are shown in Figure 18.

Equation 5: Na-K-Ca geothermometer:

$$T(°\mathrm{C}) = \frac{1647}{\left\{\log\left(\frac{Na}{K}\right) + \beta\left[log\left(\frac{Ca^{1/2}}{Na}\right) + 2.06\right] + 2.47\right\}} - 273$$

$$where\ t > 70℃$$

$$Na, Kand\ Ca = concentrations\ of\ sodium, potassium\ and\ calcium\ in\ (mg/kg)$$

$$and\ \beta = {}^{4}\!/_{3}\ if\ T < 100℃\ and\ \beta = {}^{1}\!/_{3}\ if\ T > 100℃$$

Cells within 5 km of a geothermometer data point were assigned a score from 1-5 based on temperature. The lower limit of 90^{o}C for the silica-based geothermometer was selected based on the threshold value of “moderate” geothermal resources used by the United States Geological Survey in the 2008 assessment of U.S. geothermal resources. Geothermometry estimates above 150^{o}C received the most favourable score (Table 7).

Table 7: Geothermometer scoring table

Score	SiO_2 Est. Temperature (^oC)	Na-K-Ca Est. Temperature (^oC)
0	No data	No data
1	<90	<110
2	90-120	110-130
3	120-140	130-140
4	140-160	140-150
5	>160	>150

The rasters based on the silica geothermometers (Figure 18) and the Na-K-Ca geothermometer (Figure 19) were combined into a single raster with the maximum value being stored in the final raster (Figure 20).

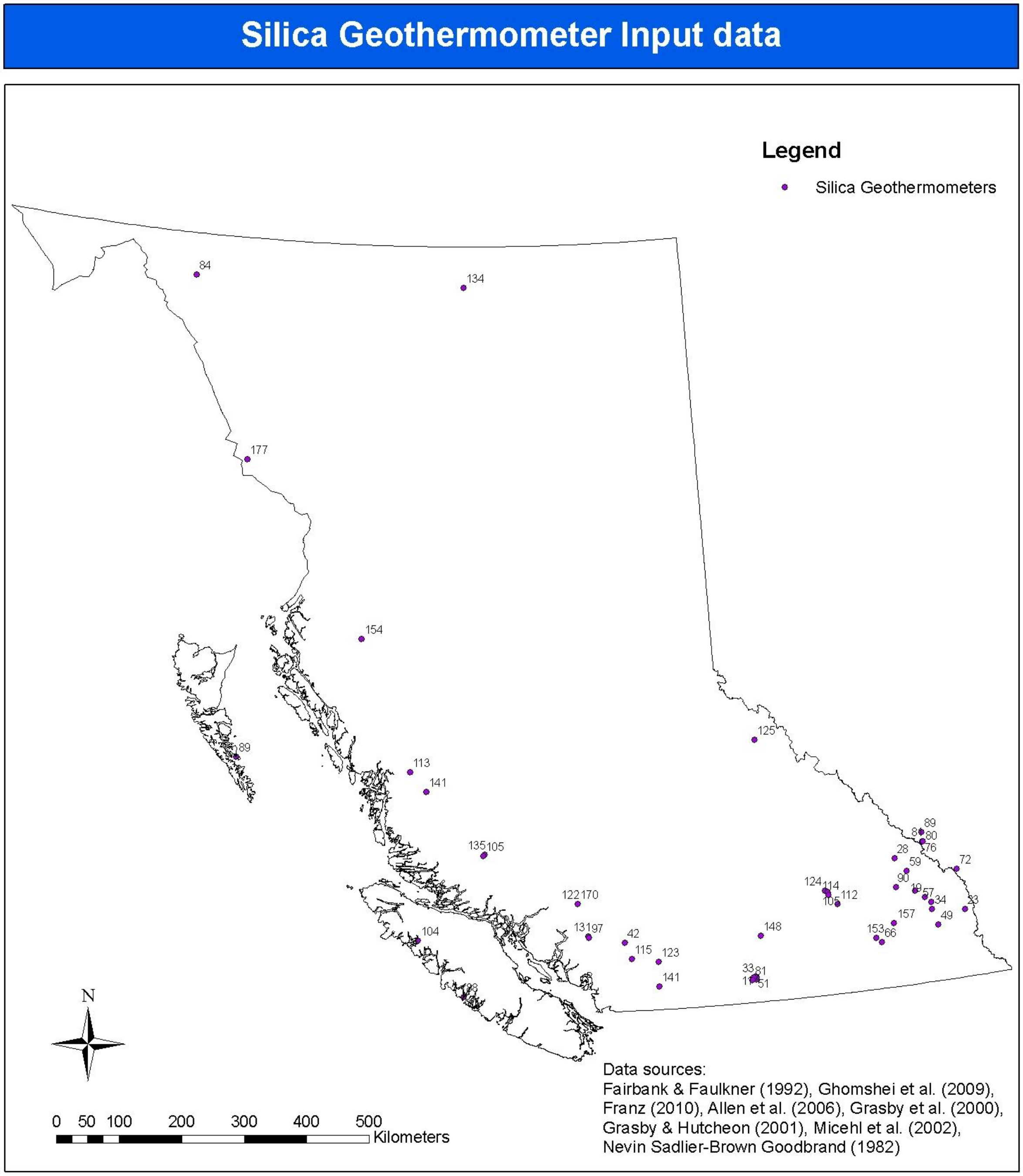

Figure 16: Geothermometer values for the silica geothermometer

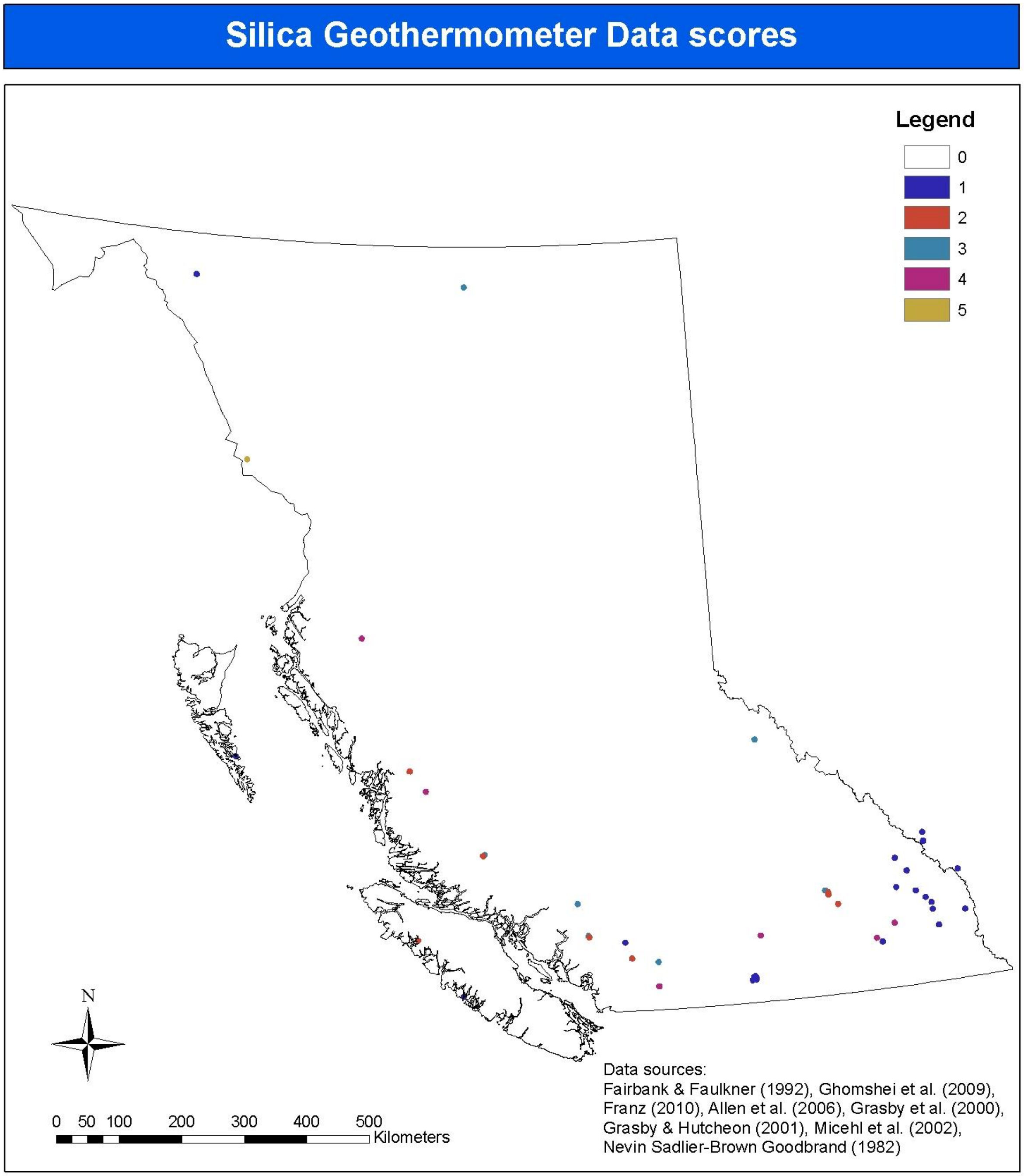

Figure 17: Output raster with scores from the silica geothermometer

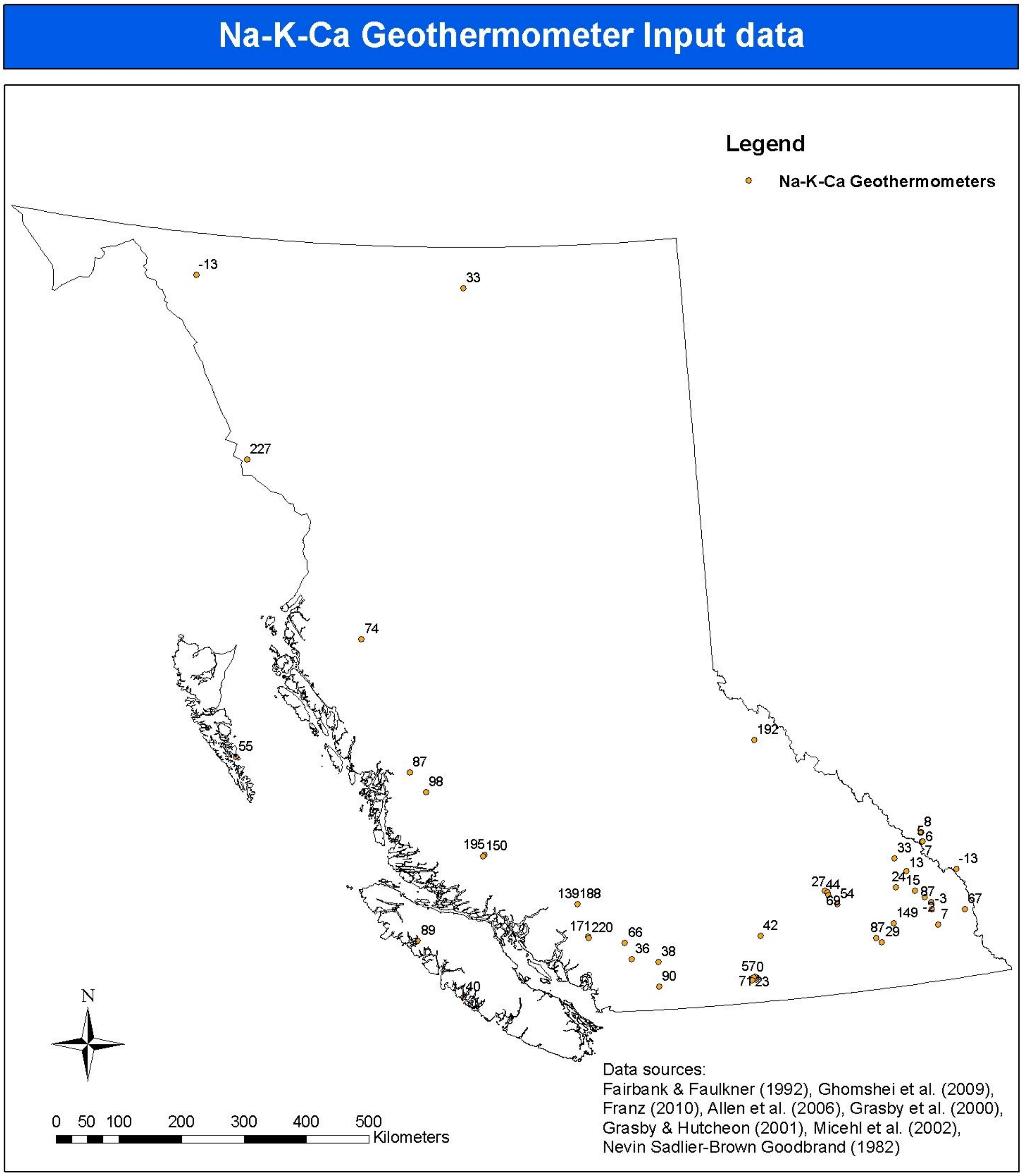

Figure 18: Input data from cation geothermometers

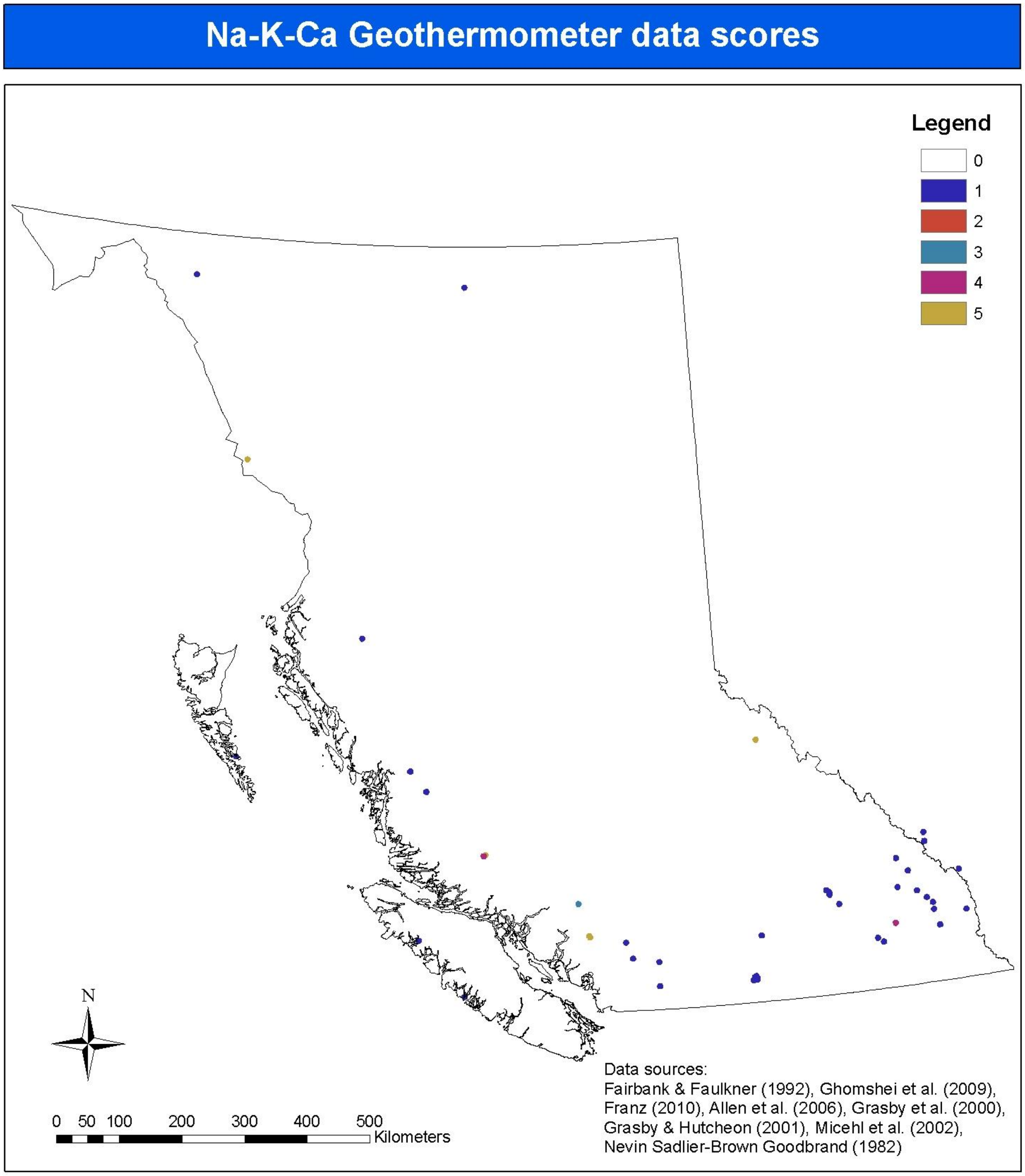

Figure 19: Raster from Na-K-Ca geothermometers

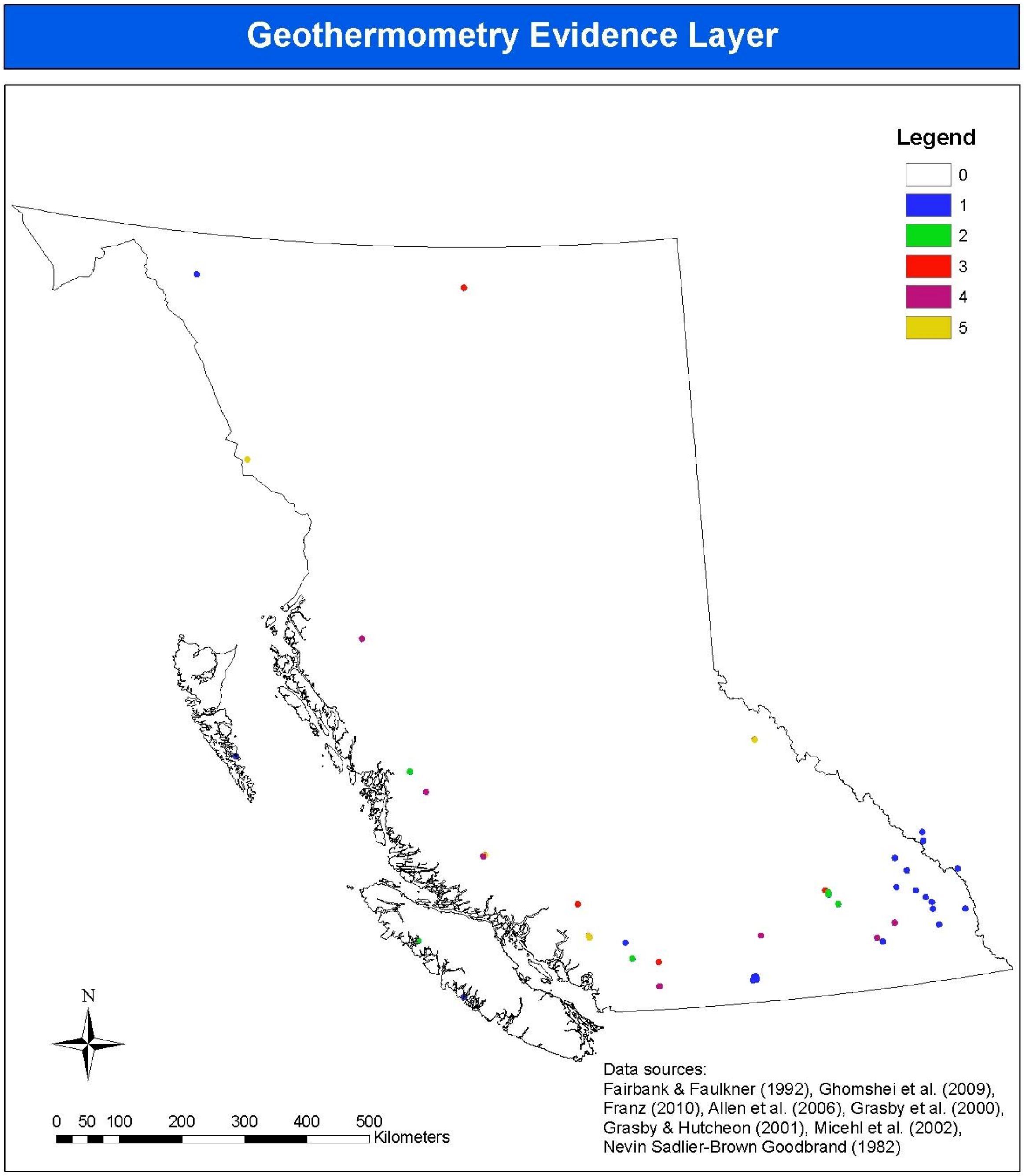

Figure 20: Geothermometry evidence layer (cell values from the maximum of either silica or Na-K-Ca geothermometer)

4.1.5 Volcanology

The world's most productive geothermal resources are closely associated with magmatic processes (Wohletz & Heiken, 1992):

- Magma-heated, dry steam resources (e.g. the Geysers, California)
- Andesitic volcanic resources (e.g. Philippines, Indonesia, Central & South America)
- Caldera resources (e.g. Medicine Lake, Valles Caldera, Los Humeros, Yellowstone; U.S.A.)
- Sedimentary-hosted, volcanic-related resources (Imperial Valley, U.S.A.)
- Oceanic-ridge, basaltic resources (Hawaii, Iceland, Azores).

The age, type of volcanic feature, size, and composition all provide an indication of the thermal history of an area with larger and younger magma bodies, generally having more heat in place. Younger volcanic features have thermal energy remaining while older features have cooled and are unlikely to host a concentration of heat suitable for geothermal power. For this reason, the Great Basin geothermal favourability map, includes volcanic features <1.5 Ma in the analysis (Coolbaugh, Zehner, Kreemer, Blackwell, & Oppliger, 2005).

The composition or SiO_2 content of a volcanic feature provides information on the thermal characteristics of a feature. For example, volcanoes with a higher SiO_2 content (i.e. rhyolite and dacite) have a higher magma viscosity and are more likely to form sub volcanic plutons that could provide significant heat for a geothermal system. Features with basaltic composition (e.g. dikes, cinder cones) have lower viscosities, do not take very long to cool to crustal-ambient temperatures, and are uncommon in continental geothermal systems.

The volcanic centers evidence layer includes data on active volcanoes from the Smithsonian Global Volcanism Program (Siebert & Simkin, 2002-) and the Volcanoes of North America book (Hickson C. ,1992)[5]. These 22 features were selected because they are the most likely to have residual heat creating a geothermal system (shown in Figure 21).

In the favourability analysis, cells within a 15 km radius (chosen based on Carranza, et al., 2008) of a volcanic feature were assigned a score from 1-5 according to the type of volcanic feature (see Table 8). Smaller features of basaltic composition received lower scores while larger features with higher silica content received higher scores. The resulting raster for the volcanic centers evidence layer is shown in Figure 22.

Table 8: Scoring table for volcanic centers

Score	Volcanic centers
0	No data
1	Pyroclastic & Cinder Cones
2	Basaltic volcanic fields, subglacial volcano
3	Shield volcano
4	Stratovolcano or Volcanic field (SiO_2>52%)
5	Complex volcano or Caldera

[5] Only major volcanoes less than 2.5 Ma are included from the Volcanoes of North America textbook.

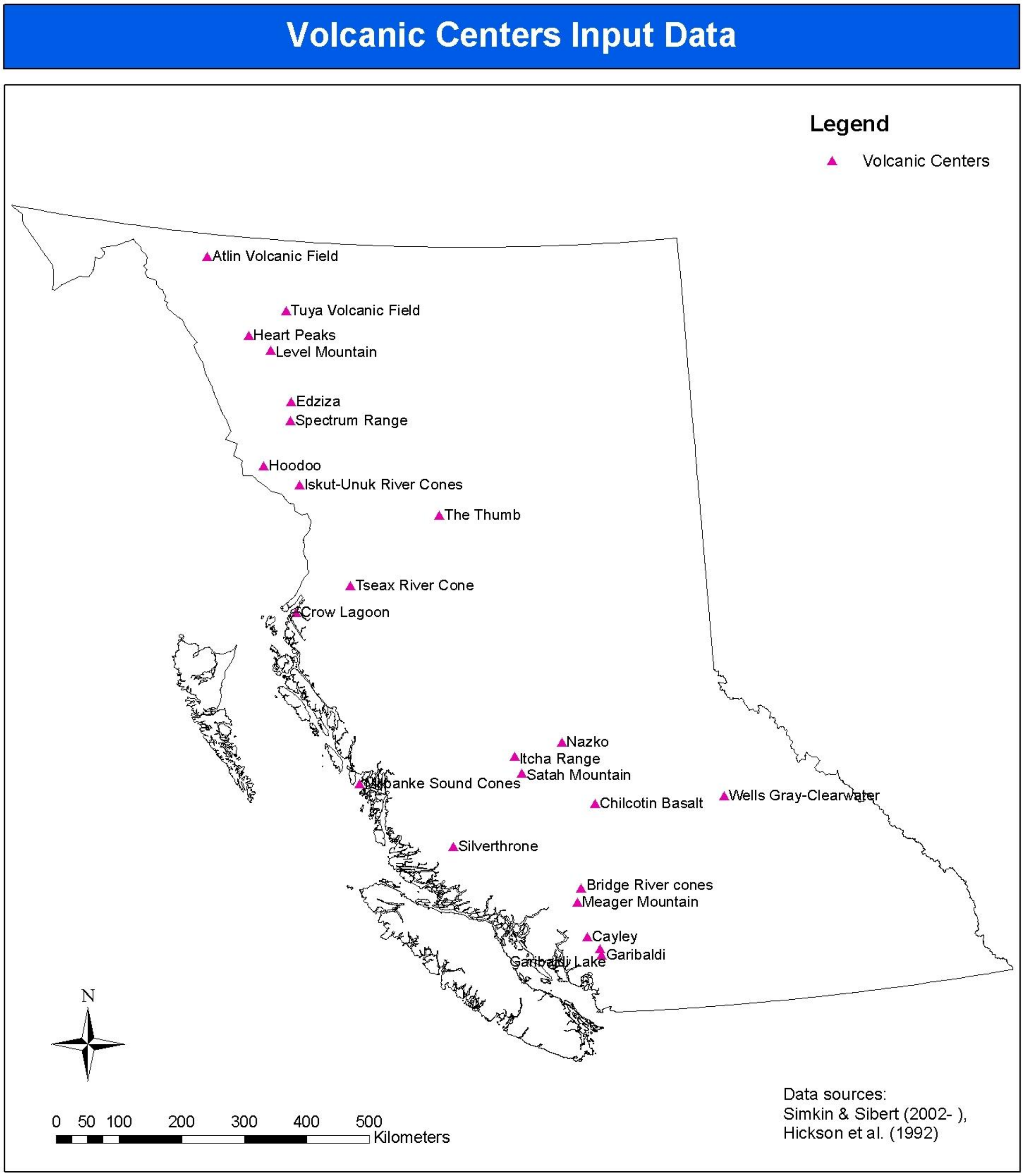

Figure 21: Volcanic centers input data

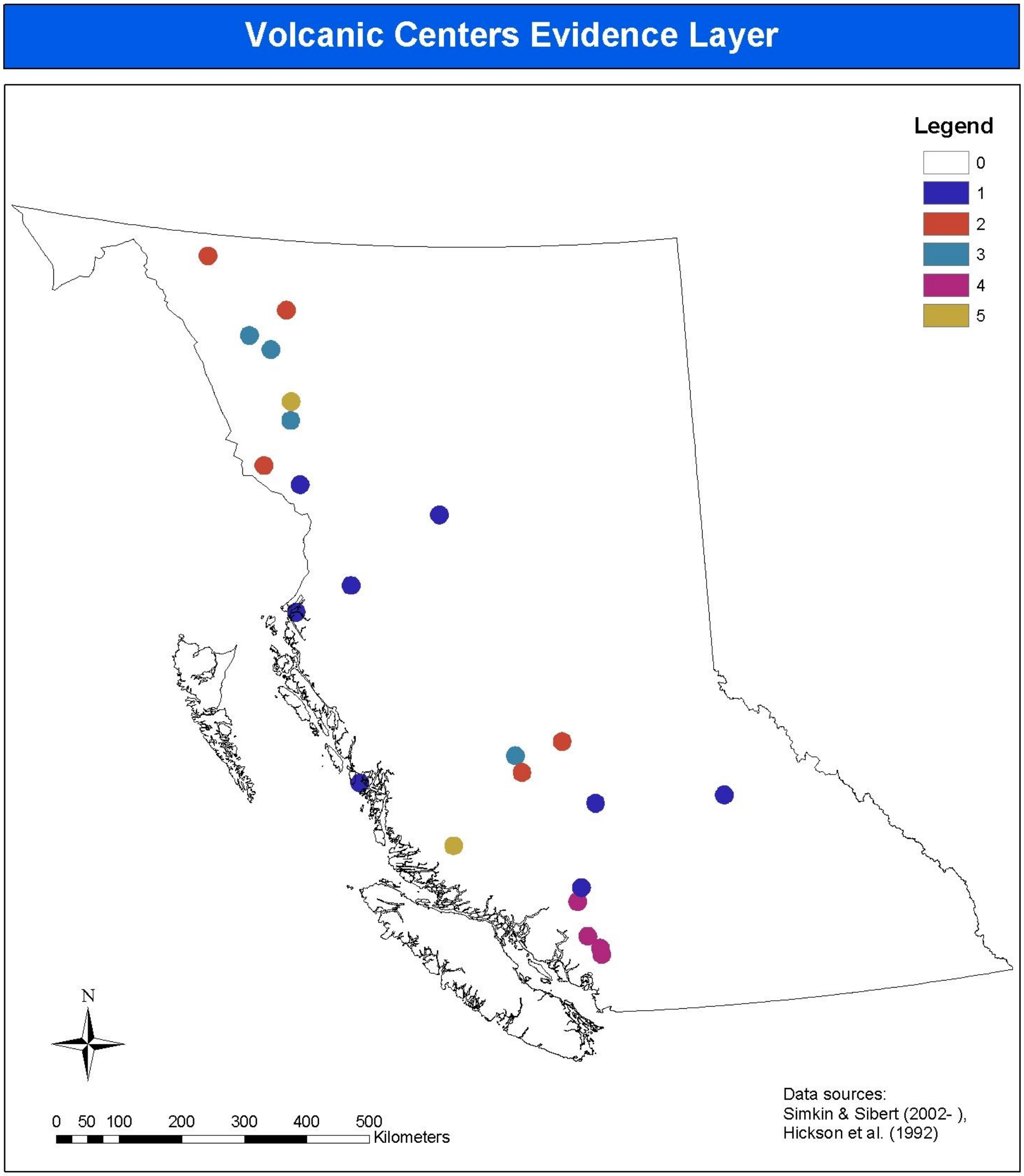

Figure 22: Volcanic centers evidence layer

4.1.6 Geology

Certain rock types are more likely to contain stored heat that could be a source of geothermal energy. Hydrothermal systems are common to young volcanic rocks, while Engineered Geothermal Systems may lie in hot sedimentary aquifers and intrusive rocks where radioactive decay contributes to heat generation. Several favourability maps incorporate geologic information into the favourability analysis: Carranza et al., (2008), Noorollahi et al. (2007) and (Yousefi, et al., 2010) use Quaternary volcanic rocks as an indicator. And, in the absence of geothermal gradient data, EBA Engineering Consultants Ltd., (2010) uses geologic provinces in the Northwest Territories as one of three evidence layers.

Rock types from the Digital Geology Map of BC (Massey, MacIntyre, Desjardins, & Cooney, 2005) were included in the favourability analysis, providing the added advantage of complete data coverage of the province (unlike other evidence layers). The five different rock types in British Columbia were used as input data (see Figure 23) for the geology evidence layer (Figure 24). This layer was converted to a raster, with the raster cells being scored from 1-5 based on the rock type and the age of the rock (Table 9).

Table 9: Geology scoring table

Score	Rock type
0	No data (unknown)
1	Sedimentary rocks, Mesozoic and older intrusives, Metamorphic and Ultramafic rocks, and Oligocene and older volcanic rocks
2	Cenozoic and younger intrusives, Miocene volcanic rocks
3	Sedimentary basins, Pliocene volcanics
4	Pleistocene volcanic rocks
5	Holocene volcanic rocks

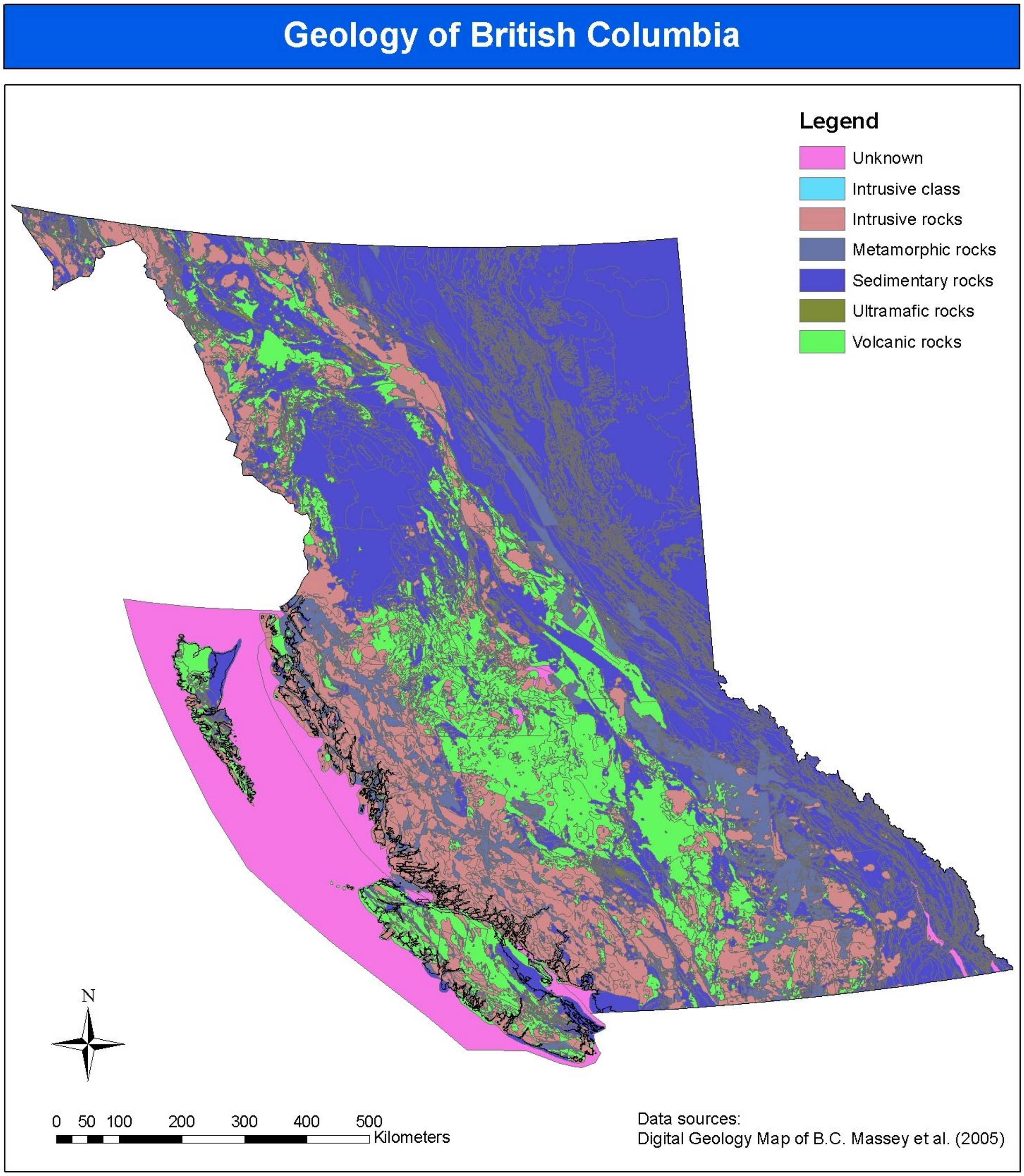

Figure 23: Rock type evidence layer input data

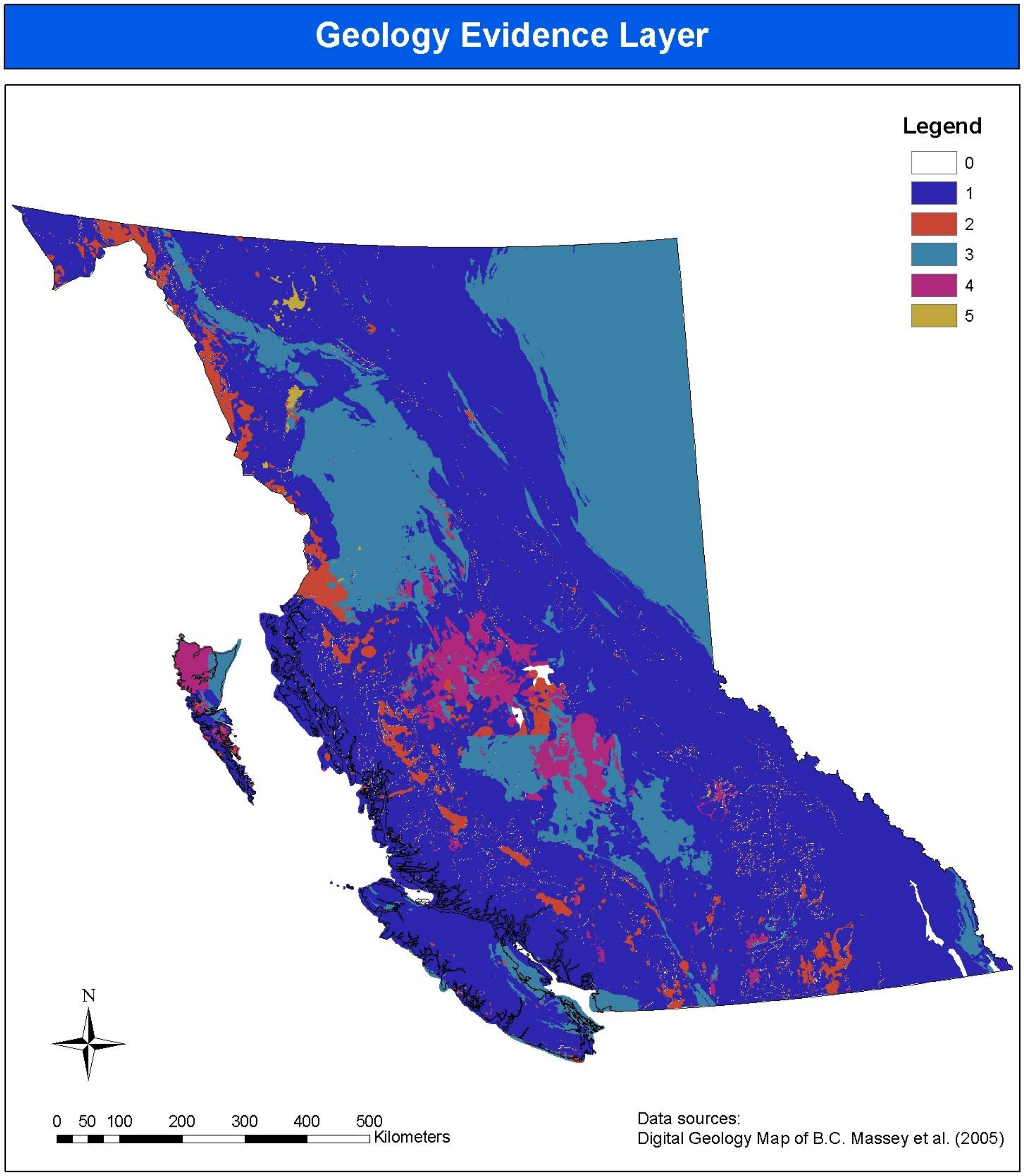

Figure 24: Geology evidence layer with scores

4.2 Permeability Indicators

4.2.1 Faults

Faults act as conduits for geothermal fluids and are commonly the targets when drilling geothermal wells to access areas of geothermal fluid up flow. In the Great Basin, “Active extensional tectonics play a key supporting role in providing the fracturing and permeability necessary for fluid circulation to form economic high temperature (>=150^{o}C) extensional geothermal systems” (Coolbaugh, Arehart, Faulds, & Garside, 2005). In these systems, priority exploration targets are areas of high heat flow, with up-flow zones of hot water that often occur at fault intersections. In the West Java favourability map, Carranza et al. (2008) demonstrate there is higher geothermal potential within 10 km of preferentially oriented faults (NE-, NNW-, or WNW-trending).

Mapped faults available in the Digital Geology Map of BC (Massey, MacIntyre, Desjardins, & Cooney, 2005), include the location of faults and their type (shown in Figure 25). A raster with 1 km X 1 km cells was created using the line density function (with a search radius of 6 km) in ArcGIS; higher values were assigned to cells with multiple faults. The search radius was selected based on the favourability map of Iran that uses a 6 km buffer around mapped faults (Yousefi, et al., 2010). The line density raster was then re-classified to normalize the scores from 1-5 using the natural breaks classification in ArcGIS (Table 10). The fault density evidence layer is shown in Figure 26.

Table 10: Fault density scoring table

Score	Fault density (line/km^2)
0	No data
1	0.1-0.06
2	0.06-0.19
3	0.19-0.37
4	0.37-0.65
5	0.65-2.04

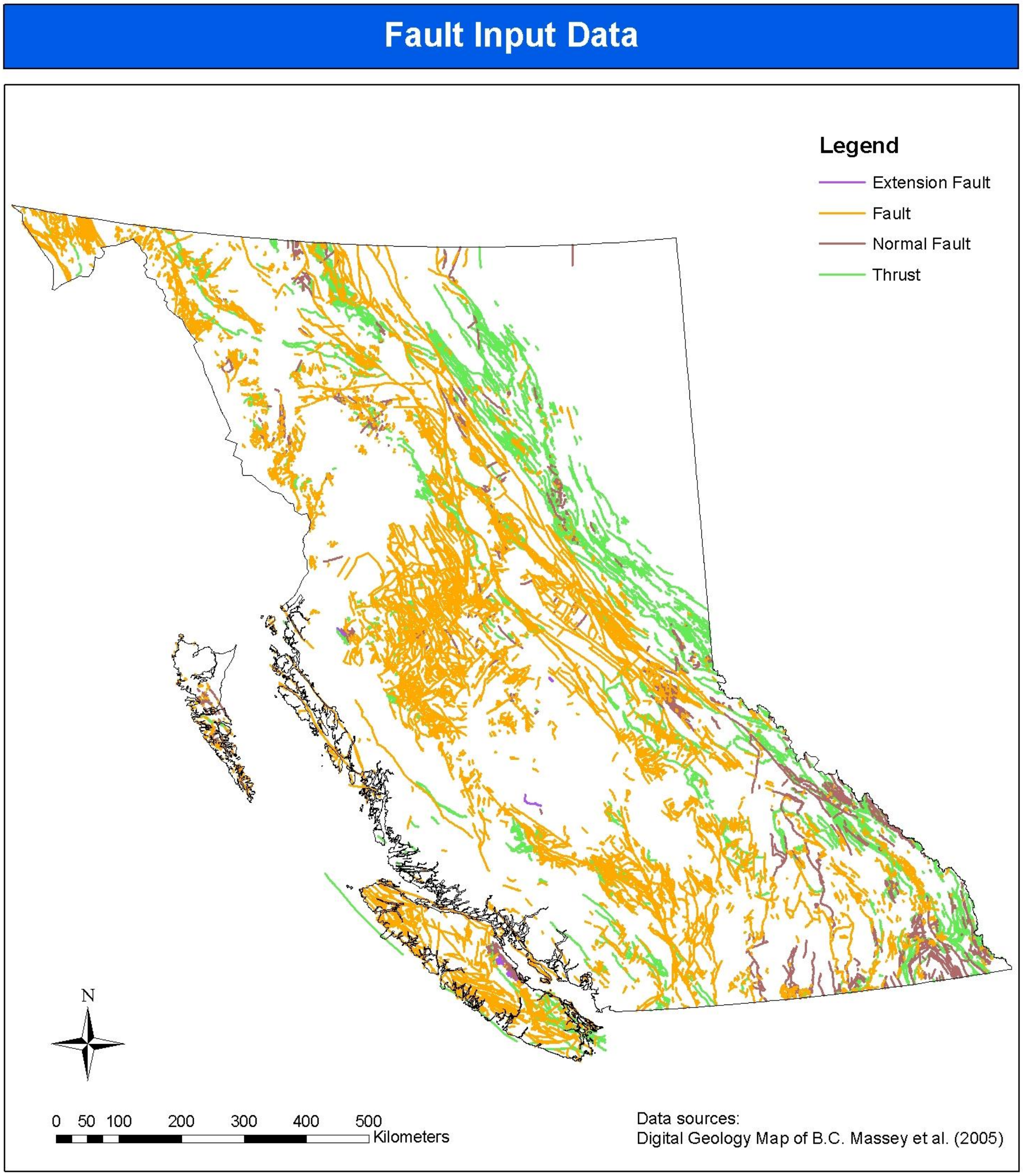

Figure 25: Input data for fault density evidence layer

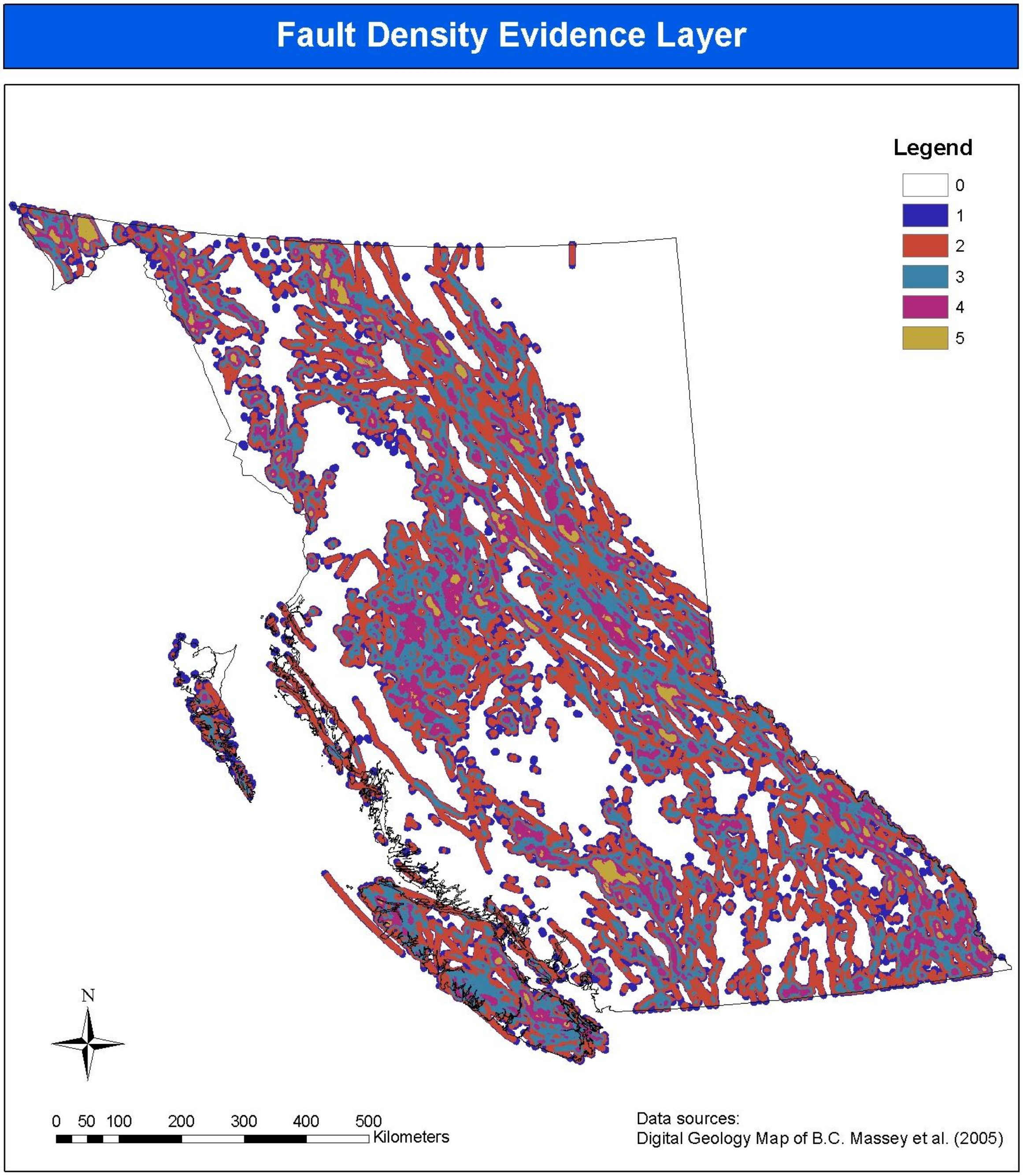

Figure 26: Fault density evidence layer

4.2.2 Earthquakes

Areas with seismic activity are indicative of active faults which are the most likely faults to provide the necessary permeability to bring geothermal fluids to the near surface. Previous work on behalf of BC Hydro and Power Authority (Nevin, Sadlier-Brown Goodbrand, 1974) plotted the epicenters of all recorded earthquakes greater than magnitude 3 in southwest BC to establish the locations of deep-seated, active faults. The results were too scattered to show a distinct pattern, but did confirm recent fault activity on major faults at the western edge of the Liilooet River region.

Earthquake data is incorporated into favourability maps of Iran, West Java, Nevada, and the Great Basin. Earthquake epicenter locations from shallow (less than 10 km) depths were found to have a negative spatial association in West Java possibly due to a poor or incomplete data set (Carranza, Wibowo, Barritt, & Sumintadireja, 2008). In the favourability map of Nevada, earthquakes with magnitudes greater than 4.0 were included with a radius of influence of 40 km; however earthquake frequency and magnitude showed the weakest contrast (meaning low correlation) of all evidence layers considered in the map (Coolbaugh, et al., 2002). Similarly, the Great Basin map used earthquakes strong enough to be detected anywhere in the Great Basin (determined to be of magnitude 4.8 or greater) as indicators for geothermal potential (Coolbaugh, Zehner, Kreemer, Blackwell, & Oppliger, 2005). For the geothermal favourability map of Iran, micro earthquakes (magnitude>4) are assigned a 5 km buffer, and macro earthquakes (magnitude>6) are assigned a 40 km buffer (Yousefi, 2010).

Earthquake data for Canada was obtained from the Geological Survey of Canada at: http://earthquakescanada.nrcan.gc.ca/zones/westcan-eng.php; search parameters used to access the data are included in Appendix C (Earthquakes Canada, 2009). Epicenter locations for earthquakes with magnitude 4 or greater were included in the analysis (Appendix C). Following the methodology of Coolbaugh, et al. (2002 and 2005), raster cell values were calculated using the Inverse Distance Weighted function in ArcGIS, with a search radius of 40 km. Cells were then re-classified by magnitude and assigned a score from 1-5 (see Figure 28 for scoring table and output raster for Earthquake evidence layer).

Table 11: Earthquake scoring table

Score	Earthquake Magnitude
0	No data
1	-
2	-
3	4-5
4	5-6
5	>6

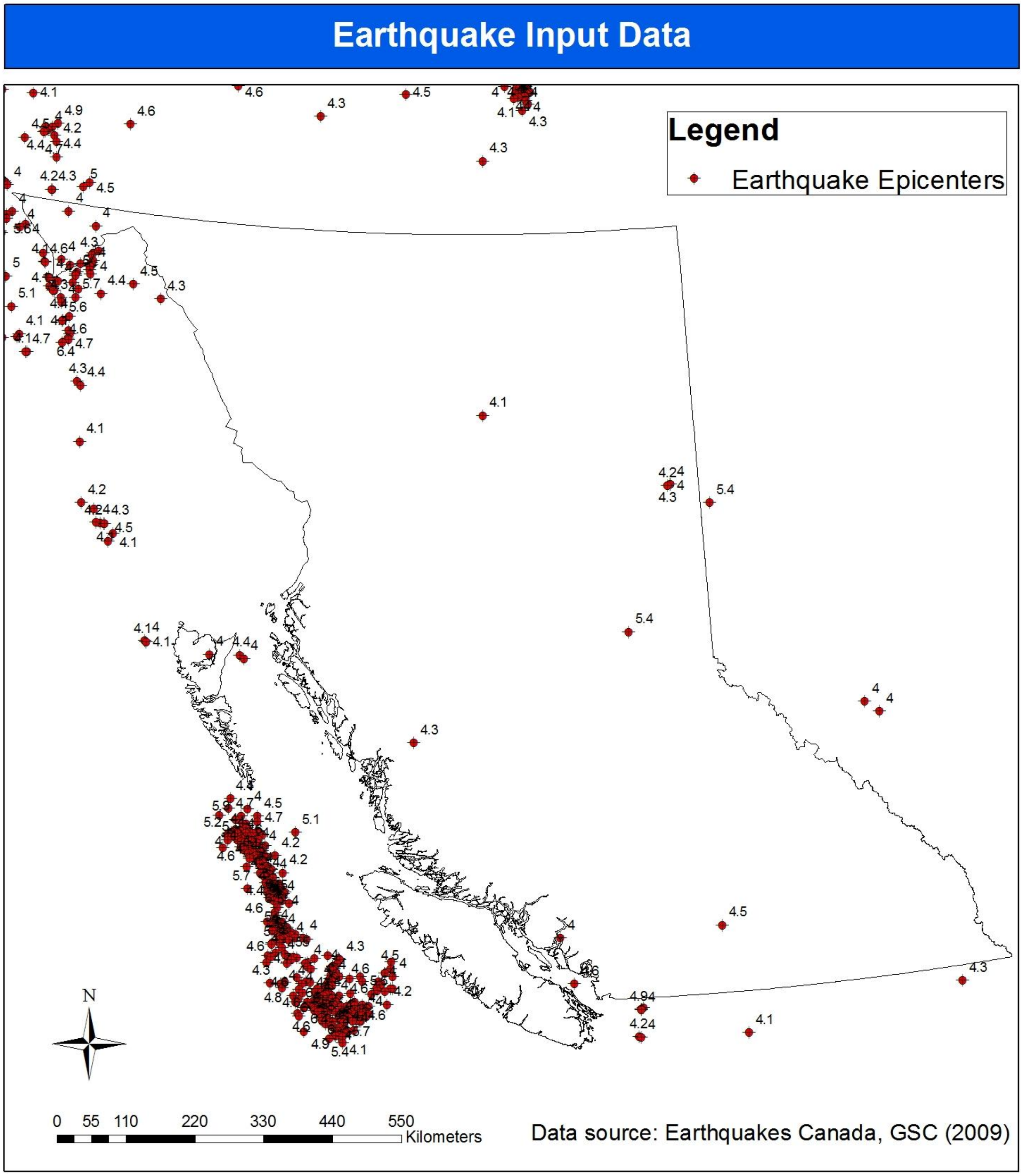

Figure 27: Input data for the earthquake evidence layer

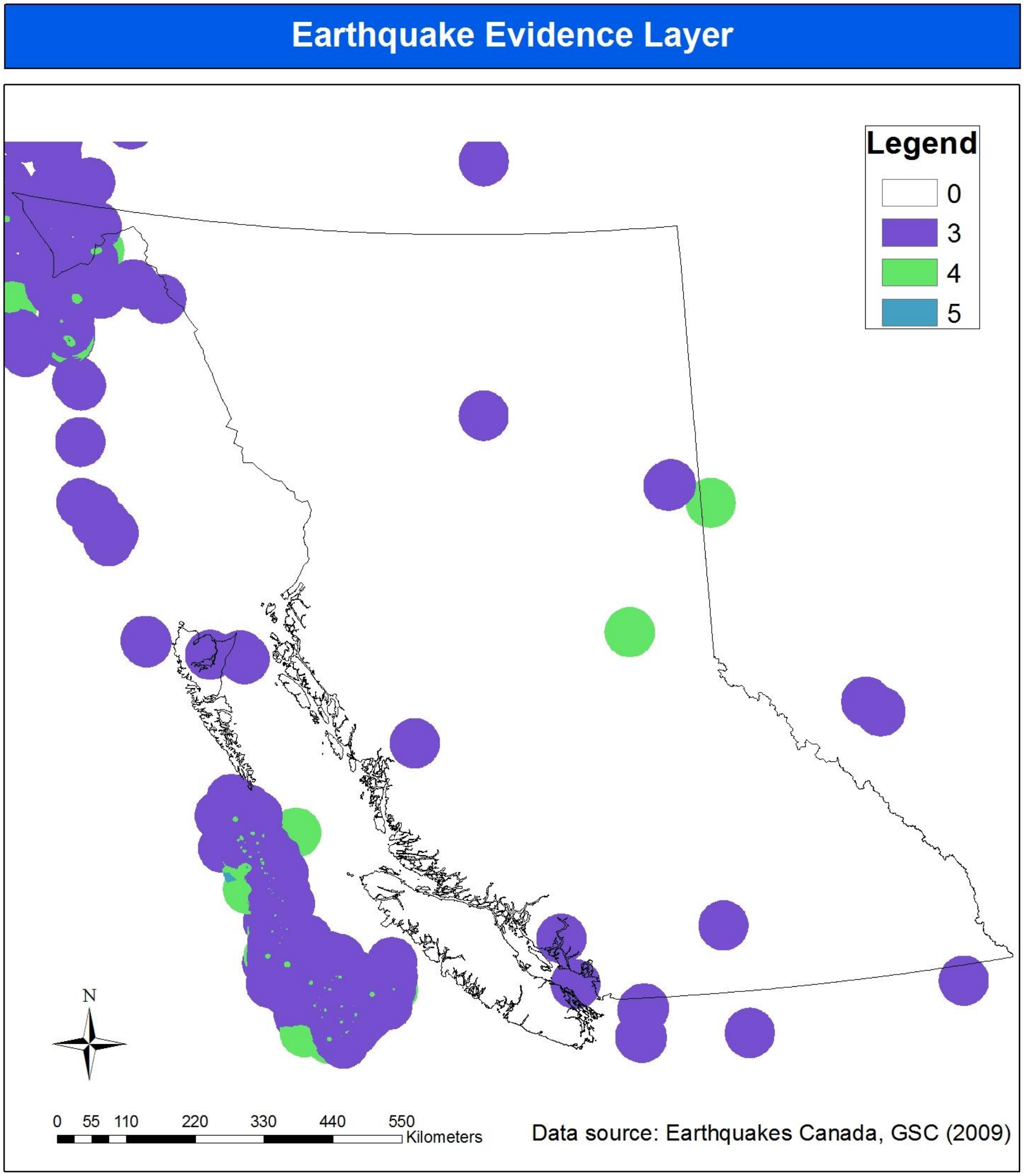

Figure 28: Earthquake evidence layer

5 Market & Infrastructure

Market and infrastructure factors are crucial, particularly when it comes to project economics, for all types of renewable energy projects. To capture this information, three evidence layers for population density, proximity to transmission, and regional pricing were combined in the market & infrastructure factor map (Figure 29).

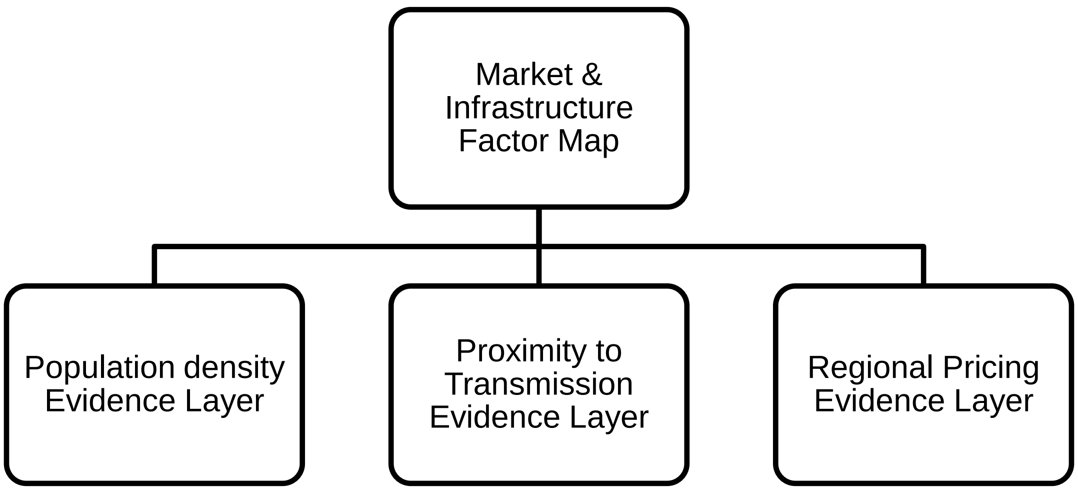

Figure 29: Evidence layers in the market & infrastructure factor map

5.1 Demand

Approximately 70-80% of BC's electrical load is located in the Lower Mainland and Vancouver Island, while most of the generation comes from facilities in the northern and southern interior (BCTC, 2010). BC Hydro dominates the electricity market, with a total capacity of 11,280 MW estimated to be 75% of the province's total which serves 94% of the population (Hoberg & MacDonald, 2010). About 5% of the province's generation capacity is met by Fortis BC, a private utility serving the Kootenay region of BC (Figure 30).

Figure 30: Fortis BC service area covering the Kootenay's region of BC (Source: Fortis BC)

Nelson Hydro serves the City of Nelson and surrounding area through its own supply and distribution systems, and purchases additional power from an independent power producer (City of Nelson). Two mining companies (Rio Tinto Alcan and Teck), generate their own power, which accounts for approximately

20% of BC's total generation (Figure 31, modified after (Hoberg & MacDonald, 2010). The remaining capacity is imported either from Alberta or from the United States. It is difficult to quantify the precise amount of power the province imports due to the complex trading patterns for electricity, and the confusion associated with the Canadian Entitlement. As part of the Columbia River Treaty, the Canadian Entitlement clause allots over 1,100 MW of electricity to British Columbia in exchange for installing dams on 3 of its rivers to assist the U.S.A. in flood control and power generation. This power is not actually used in British Columbia; rather it is sold for revenue on the spot-market by a BC Hydro subsidiary PowerEx. Whether or not electricity from the Canadian Entitlement is included in the calculations, it is clear that there has been a deteriorating trade balance between imports and exports in BC since 2000. Furthermore, BC has been a net importer of electricity for 3 out of the last 5 years, and 4 out of the last 6 years (Hoberg & MacDonald, 2010).

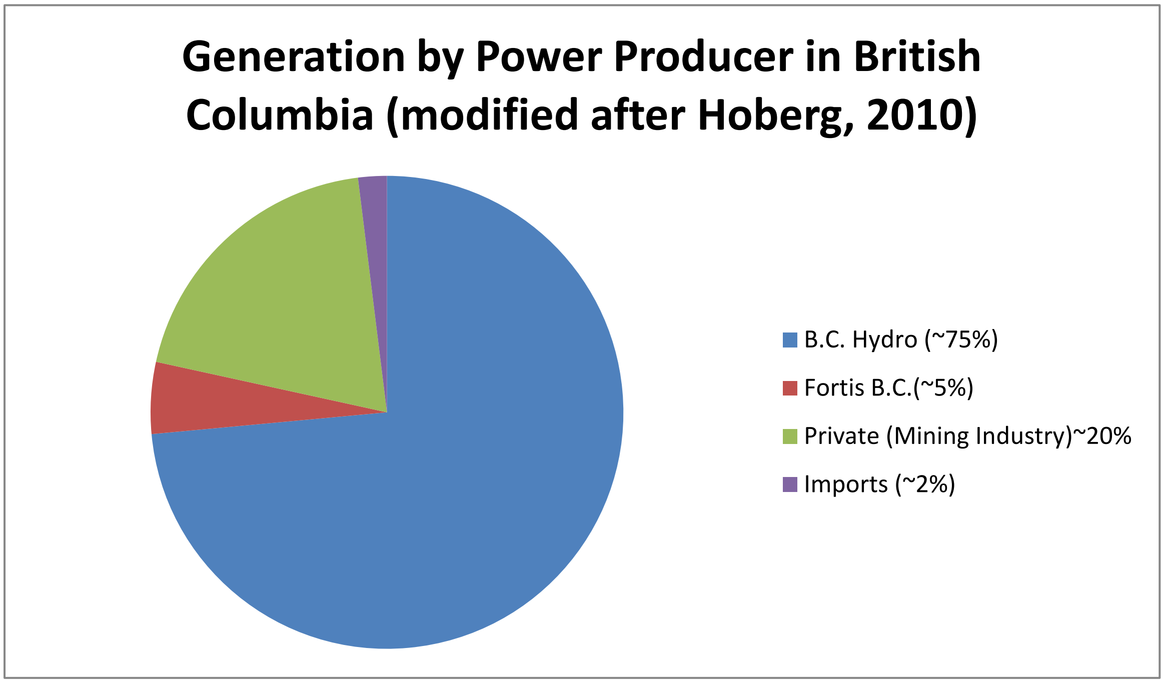

Figure 31: Power generation in BC, values are approximate due to trade by PowerEx, (total does not = 100%). Modified after Hoberg & MacDonald, 2010.

5.1.1 Population Density

Energy projects that are close to the energy-user are favourable since transmission line losses can be minimized. British Columbia's biggest load is in the Lower Mainland and Vancouver Island, so power typically flows from the north to the south along transmission lines. Areas with the higher population density have higher residential and commercial demand for electricity.

The population density evidence layer uses 2006 Census data from Statistics Canada (2007) to calculate the population density for Dissemination

Areas[6] in B.C. The population density values were converted to a raster with cell size of 1 km X 1 km (Figure 32). The raster was then re-classified into 5 classes using the natural breaks method in ArcGIS (Table 12), areas with the highest population density were assigned a score of 5 (see inset map in Figure 33) and the lowest population density a score of 1.

Table 12: Population density scoring table

Score	Population density (population/m^2)
0	No data
1	0-0.000688978
2	0.000688978-0.002329124
3	0.002329124-0.004985937
4	0.004985937-0.011028367
5	0.011028367- 0.028375920

[6] A dissemination area is a small area composed of one or more neighbouring blocks, with a population of 400 to 700 persons. All of Canada is divided into dissemination areas. (Statistics Canada, 2007)

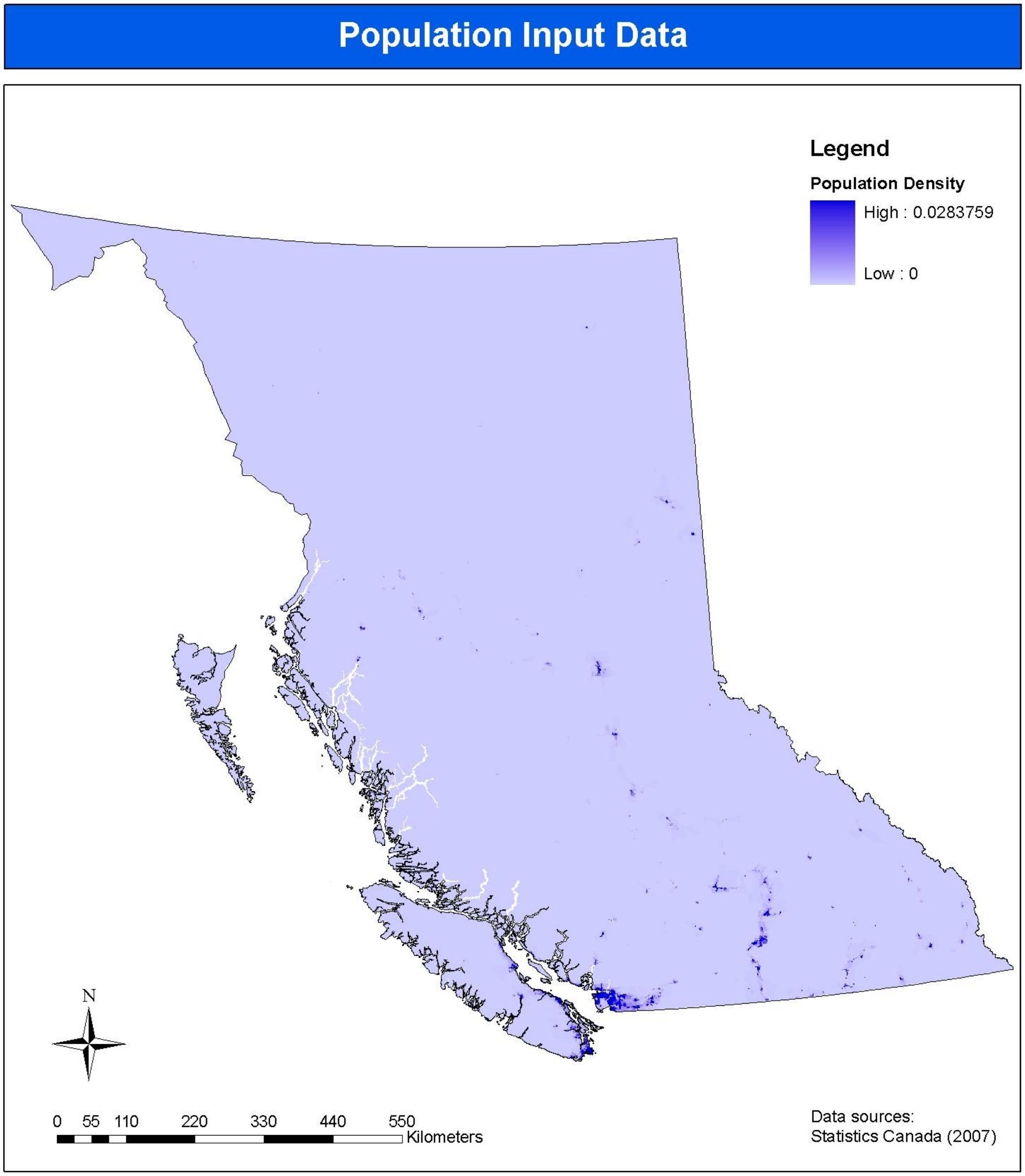

Figure 32: Input data for population density evidence layer

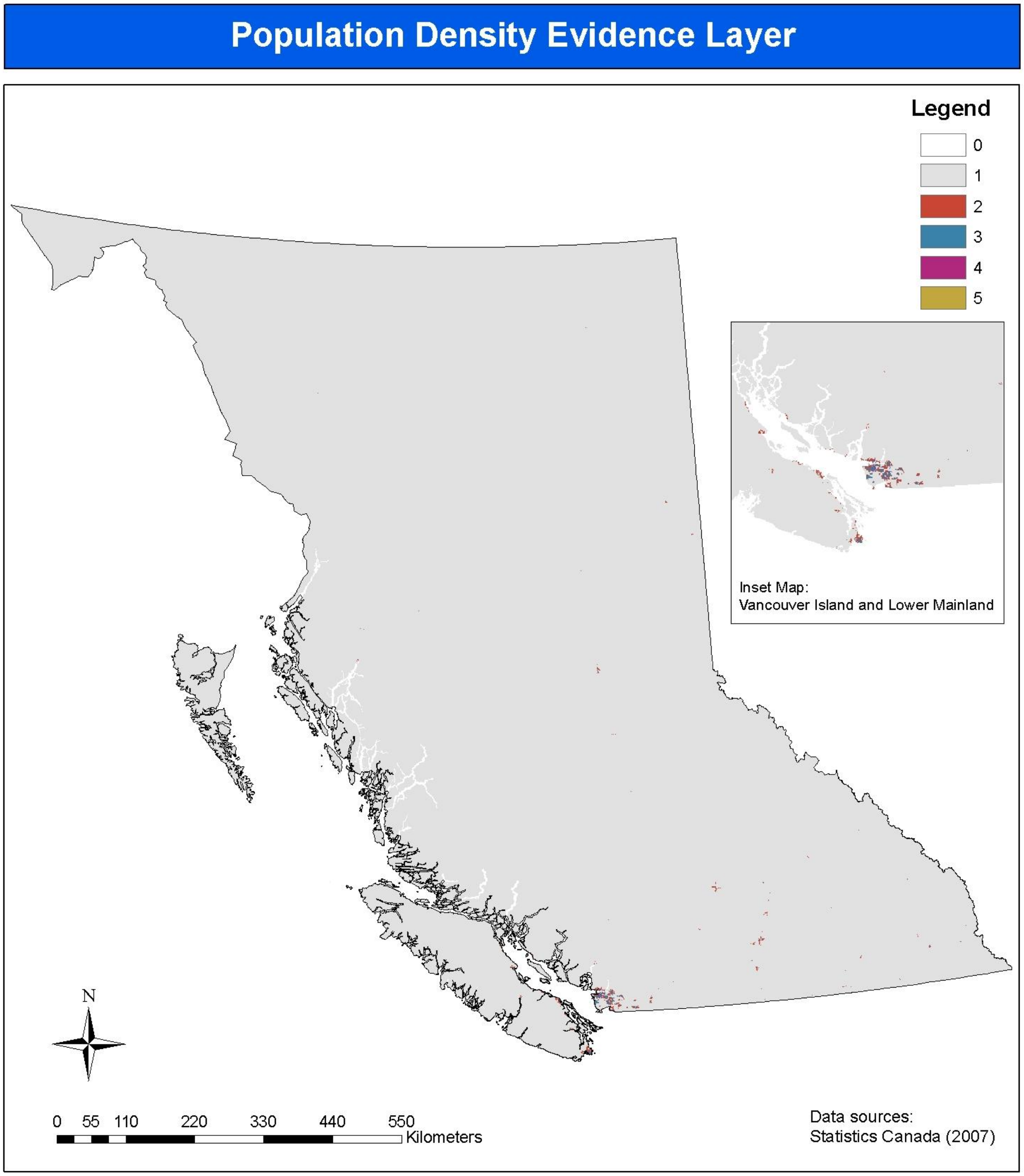

Figure 33: Population density evidence layer with inset map of the Lower Mainland and Vancouver Island

5.1.2 Industrial Activity

Another major component of the electricity load in BC is from industrial sources, comprised of three major sectors in British Columbia: forestry, mining, and oil & gas. This sector accounts for 37% of BC Hydro's domestic electricity sales, of which forestry accounts for 60% (2008 LTAP, BC Hydro). Mining and processing facilities have large electricity loads, for example, Highland Valley Copper is BC Hydro's single largest customer. A complete data set of locations of industrial activity was not publicly available, and thus is not incorporated into the market and infrastructure factor map at this time. While the forestry sector is currently suffering in BC, future work may consider the location of geothermal resources with existing and future mineral exploration or oil and gas projects that tend to be energy-intensive. Geothermal power and heat could be used for powering these operations and also provide for heat for processing.

5.2 Price

Electricity pricing in Canada varies by province or territory according to the volume and type of available generation and whether prices are market-based or regulated (National Energy Board, n.d.). While Alberta has completely restructured its electricity market and Ontario partially, British Columbia remains a regulated market. The regulator, British Columbia Utilities Commission (BCUC) acts to protect rate payers and is responsible for setting prices meant to cover costs of generation and distribution, and allow for a reasonable rate of return to investors.

5.2.1 Cost of Geothermal Power

Geothermal power has one of the lowest levelized unit costs of all energy types. High capital costs are off-set by zero fuel costs and minimal operation and maintenance costs over the project lifetime. The cost of geothermal development is divided into three categories: (1) surface exploration, (2) drilling, and (3) construction of surface installations. The latter two categories are each responsible for up to approximately 40% of total costs, respectively (Barbier, 2002). When compared on a levelized unit cost[7], geothermal is very cost-competitive, particularly relative to other renewable energy alternatives. Table 13 shows geothermal has a cost of 5.09 cents/kWh, one of the lowest out of all technologies considered. It is important to note that these costs will be affected in the future by inflation, changes in fuel costs, technological improvement, achieving economies of scale/market penetration, and the price of carbon. Since geothermal energy does not require fuel sources and does not emit significant amounts of carbon, it is expected geothermal will remain or improve its position as a cost-competitive energy source.

Despite this low levelized energy cost for geothermal, the high capital costs and perceived risk of geothermal drilling leads to cautious investors.

[7] The levelized unit cost is calculated from capital costs annualized over the expected project life (using a discount rate of 8%) plus fixed and variable operation and maintenance costs and decommissioning costs.

Table 13: Levelized unit electricity cost by energy source (modified after Hatch Energy, 2008)

Energy source	Levelized unit electricity cost (cents/kWh)
Remote diesel	32.16
Coal	6.24
Conventional Gas combined cycle	9.80
Natural Gas	6.81
Conventional Hydro	5.30
Small hydro (run-of-river)	7.76
Biomass	3.86
Wind	10.88
Solar PV	63.66
Geothermal	5.09

5.2.2 Power Costs in BC

BC electricity prices are among the lowest in Canada, at 6.27 cents/kWh for residential consumers using less than 675 kWh per month and 8.27 cents for those using more than 675 kWh; users are also subject to $3.77 fixed charge (Healey, 2010). Rates for industrial and commercial customers are significantly lower (Healey, 2010). The price paid by rate payers is an average of lower-cost heritage assets (large hydro projects built in the 1970s) and new, higher-priced renewable alternatives coming online. The current power acquisition and pricing scheme for power projects is such that independent power producers (IPPs) can submit proposals for projects to the utility (BC Hydro) when there is a clean power call. Broad criteria used by BC Hydro in the selection process includes: resource risk, development risk, and price. Prices paid to the developer are negotiated on a project specific basis. In the most recent Clean Power Call, these prices ranged from $105.36/MWh to $133.80/MWh for firm energy (BC Hydro, 2010). The price is based on the developer's project cost, the cost of transmission to the point of interconnection, and costs to BC Hydro (BC Hydro, 2010).

The main costs to BC Hydro are: line losses, network upgrade costs, and the cost of incremental firm transmission (CIFT). Line losses occur as a result of the resistance to flow along transmission lines carrying the electricity. This resistance is proportional to the length of the line and inversely proportional to the cross-sectional area of the line (Hatch Energy, 2008) and leads to power (and revenue) losses the further the power has to travel. Network upgrade costs are incurred when a new project connects to the existing transmission system and the infrastructure needs to be upgraded to accommodate the additional electricity. CIFT costs incorporate the cost of moving electricity between regions and the additional room that may be required for the bulk system lines[8].

For larger projects, the total cost due to these factors (and the effect on the price paid to IPPs) is usually determined on a project-specific basis. However, for smaller (<15 MW projects), there is a Standard Offer Program (SOP) with pricing by region (BC Hydro, 2010). The SOP regional pricing values

[8] Cost of Incremental Firm Transmission (CIFT) is the incremental cost on the bulk system of getting the electricity from the plant gate to where the incremental load is expected to occur (currently assumed to be Lower Mainland). (BC Hydro, 2010)

(shown in Figure 34) are a reflection of the value the utility places on power from different regions (personal communication, David Ingleson, BC Hydro) and are incorporated in the market and infrastructure factor map.

SOP regions in Figure 34 were digitized and the boundaries between regions were interpreted in order to extend the regions over the entire province; the digitized version is shown in Figure 35. Regions with prices above $100/MWh were assigned a score of 5, and all other regions were assigned a score of 4 (Table 14).

Table 14: Regional price scoring table

Region	Price ($/MWh)	Score
Vancouver Island (VI)	102.25	5
Lower Mainland (LM)	103.69	5
Kelly/Nicola (KN)	97.02	4
Central Interior (CI)	99.26	4
Peace Region (PR)	94.86	4
North Coast (NC)	96.17	4
South Interior (SI)	98.98	4
East Kootenay (EK)	102.18	5

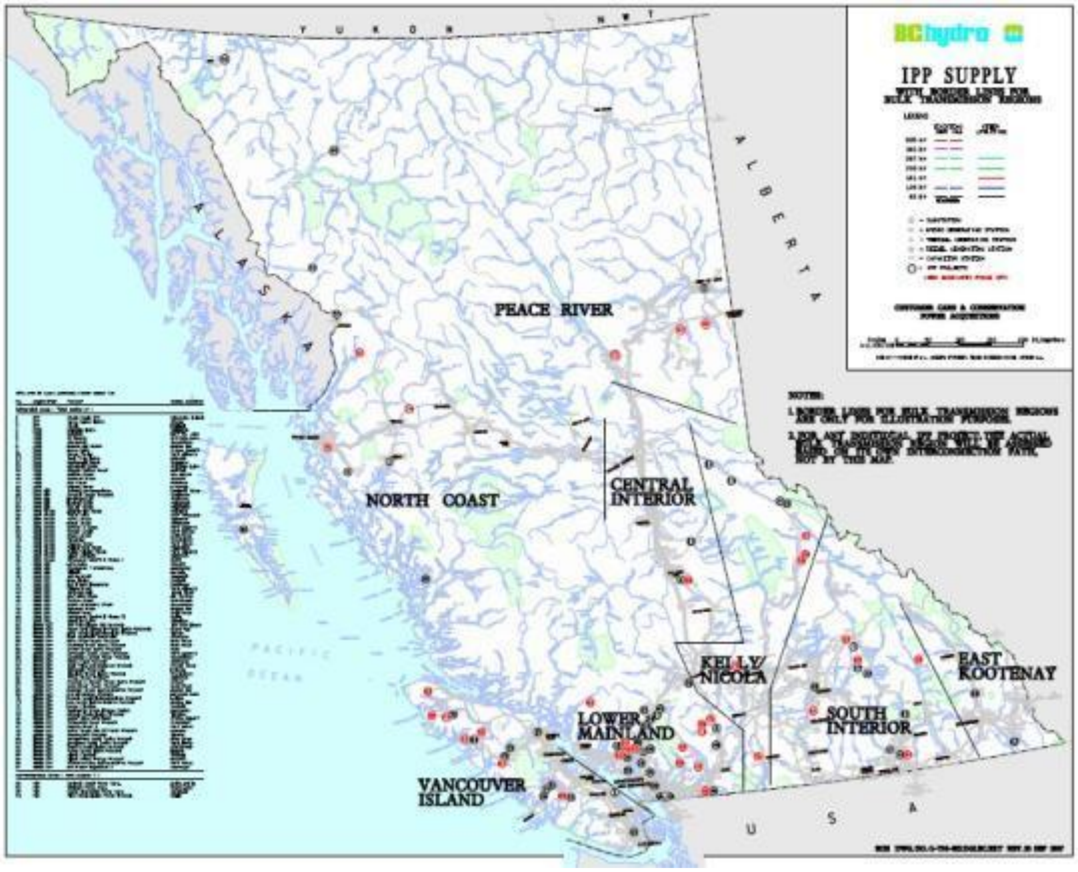

Figure 34: Map of SOP regions (Source: BC Hydro, 2007)

Figure 35: Digitized version of SOP regional pricing, with interpretations of regions; modified after BC Hydro 2010

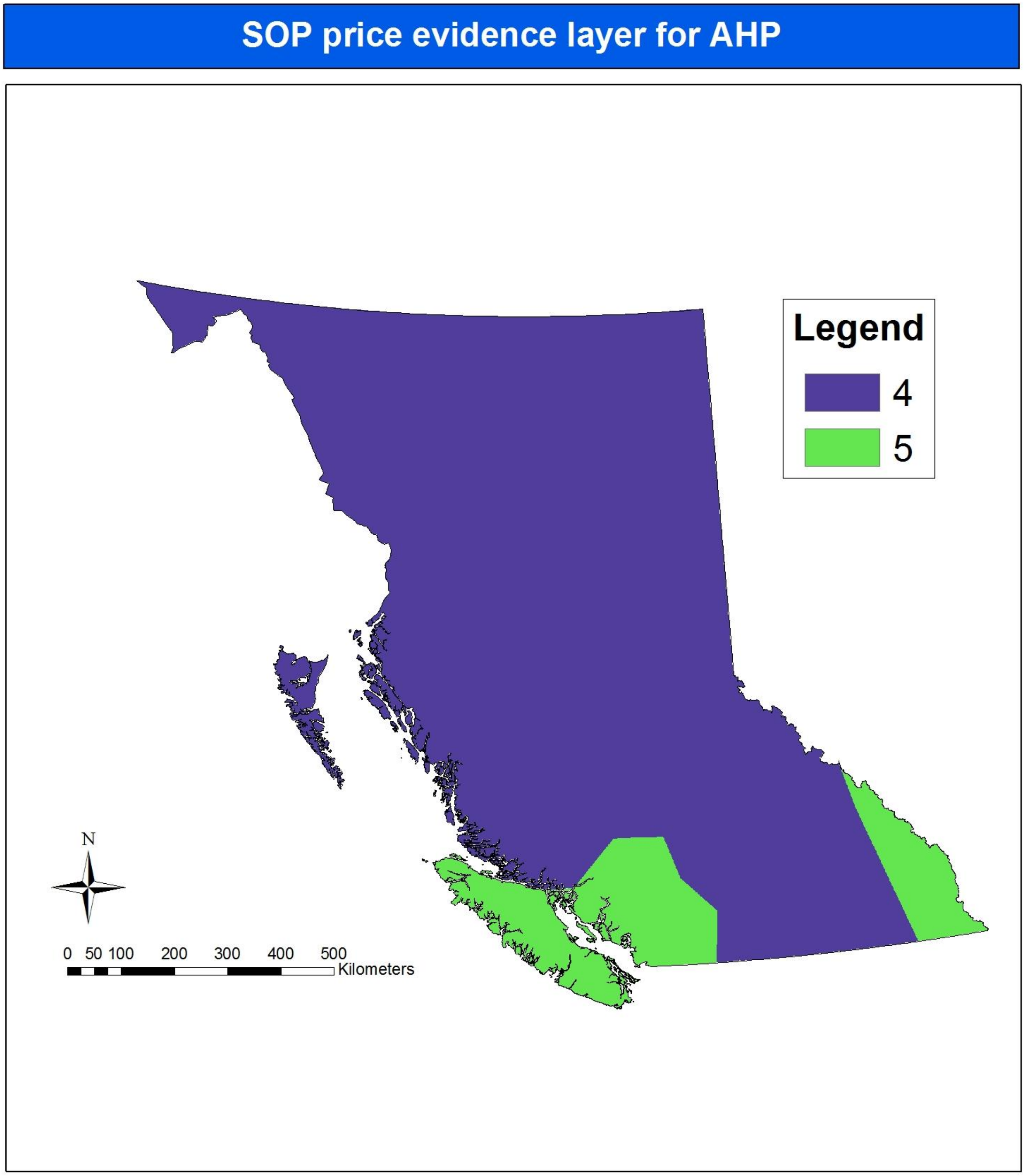

Figure 36: Pricing evidence layer based on SOP values

5.3 Transmission

Infrastructure plays a vital role in the use of power. High voltage transmission lines move electricity from generating stations to distribution substations where it is transformed to lower voltages for distribution to customers. The presence of pre-existing infrastructure near a potential power generation project is extremely beneficial, particularly for improving project economics, but also for avoiding the environmental impact of new transmission lines. The current grid serves the Lower Mainland, southeast BC, the interior, a portion of northeast BC, and Vancouver Island. The transmission system consists of 18,000 km of lines and underwater cable with voltages ranging from 69 to 500 kV (BCTC, n.d.). FortisBC manages 1,450 km of high-voltage transmission lines which operate synchronously with the BC Hydro transmission system operated by the British Columbia Transmission Corporation. A new 287 kV, 335 km, publicly owned transmission line from Skeena Substation (near Terrace) to Bob Quinn Lake (Figure 37) called the Northwest Transmission Line is scheduled to begin construction in late 2010 (BC Hydro, 2010). This line will provide power to several mining projects in the northern part of the province and may provide opportunities for geothermal projects in that area to connect to the grid.

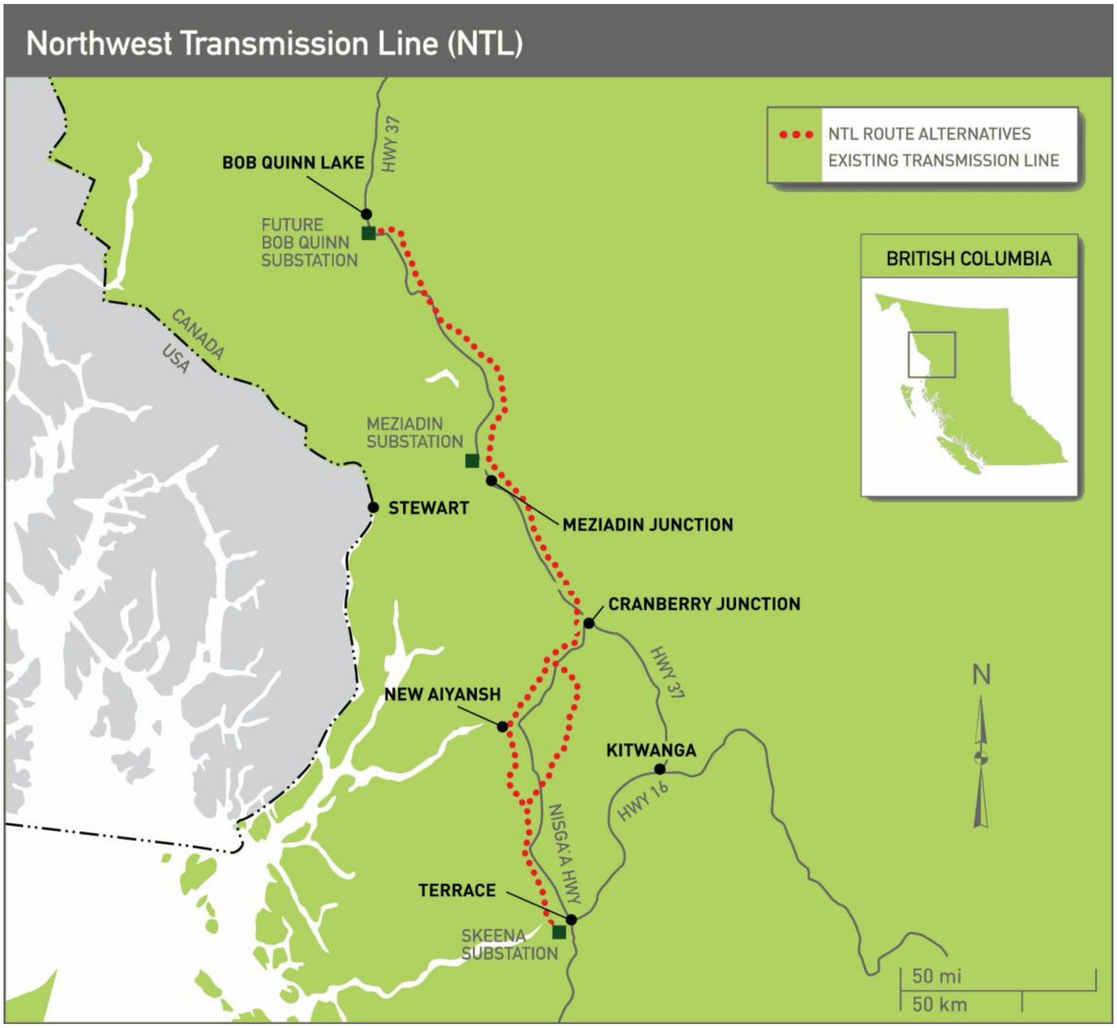

Figure 37: Planned northwest transmission line, (Source: BC Hydro, 2010)

British Columbia is currently connected to Alberta through two 138 kV lines and one 500 kV line. In addition, two 500 kV lines and two 230 kV lines connect BC to the United States. A private transmission line also crosses the U.S.A. border at the Waneta Dam near Trail, BC and the British Columbia grid is connected to Alberta near Cranbook. These connections allow BC to import and export power either to meet BC's electricity needs and to generate revenue. The import/export is limited by the maximum available transfer capacity (ATC)[9]. For BC to the U.S.A. the ATC is 3,150 MW in a north-to-south direction, and 2,000 MW in the opposite direction. Between Alberta and BC, the ATC is 760 MW in an east-to-west direction, and 600 MW west-to-east (Sopinka & Cornelis van Kooten, 2010). Assuming there is sufficient capacity on these lines, the cross-border interconnections would allow geothermal power generated in BC to be transferred to other regions.

The transfer capacity of a transmission line is dependent on many parameters: voltage, line length, conductor size used and whether it is compensated with shunt and/or series devices like series capacitor banks (personal communication, Pat Herrington, BC Hydro). One may assume that higher voltage lines would have higher transfer capacity and thus would be more favourable; however this may not be the case. Specific data on the capacity of each line is not available for the current BC grid. (Only estimates for cut planes through the bulk transmission system have been made, see: BCTC, 2008. A feasibility study and system impact study are required for individual projects, and since capacity issues are addressed on a project specific basis, all transmission lines were treated equally (i.e. no preference/higher score was given for lines of higher voltage) in the favourability analysis.

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[9] The available transfer capacity (ATC) is the maximum power that can flow along the transmission interties.

Geothermal developers are responsible for building transmission up to the point of interconnection, thus a project close to the existing grid is significantly more economically favourable. The cost of a particular line depends on many parameters such as line length, voltage level, terrain, ampacity and how much of the associated substation and other equipment is included in the cost (e.g. circuit breakers, protection, control and communications equipment, etc); (pers. comm. Pat Herrington, BC Hydro). On average, 1 km of transmission costs ~$1 million[10], and as an economic rule of thumb, 1 km of transmission can be built per 1 MW of power generation (pers. comm. Dr. Mory Ghomshei, UBC). Therefore, assuming a 100 MW project, a reasonable distance for building new transmission to interconnect with existing lines is 100 km. In the transmission evidence layer, cells up to 100 km from an existing transmission line (Figure 38) are assigned a score from 1-5 based on the distance to the transmission line (Table 15). The resulting transmission evidence layer is shown in Figure 39.

Table 15: Transmission scoring table

Score	Distance to Transmission Line (km)
0	No data
5	0-10
4	10-25
3	25-50

[10] The most recent estimate for a new transmission line in BC is the Columbia Valley Transmission line proposal. The high-level, planning cost estimates for the 230 kV, 112 km transmission line was $ 78.27 million (including 20% contingency, inflation, overhead, etc.) which is a per-kilometer cost of ~$0.7 million (BCTC, 2010).

Score	Distance to Transmission Line (km)
2	50-75
1	75-100

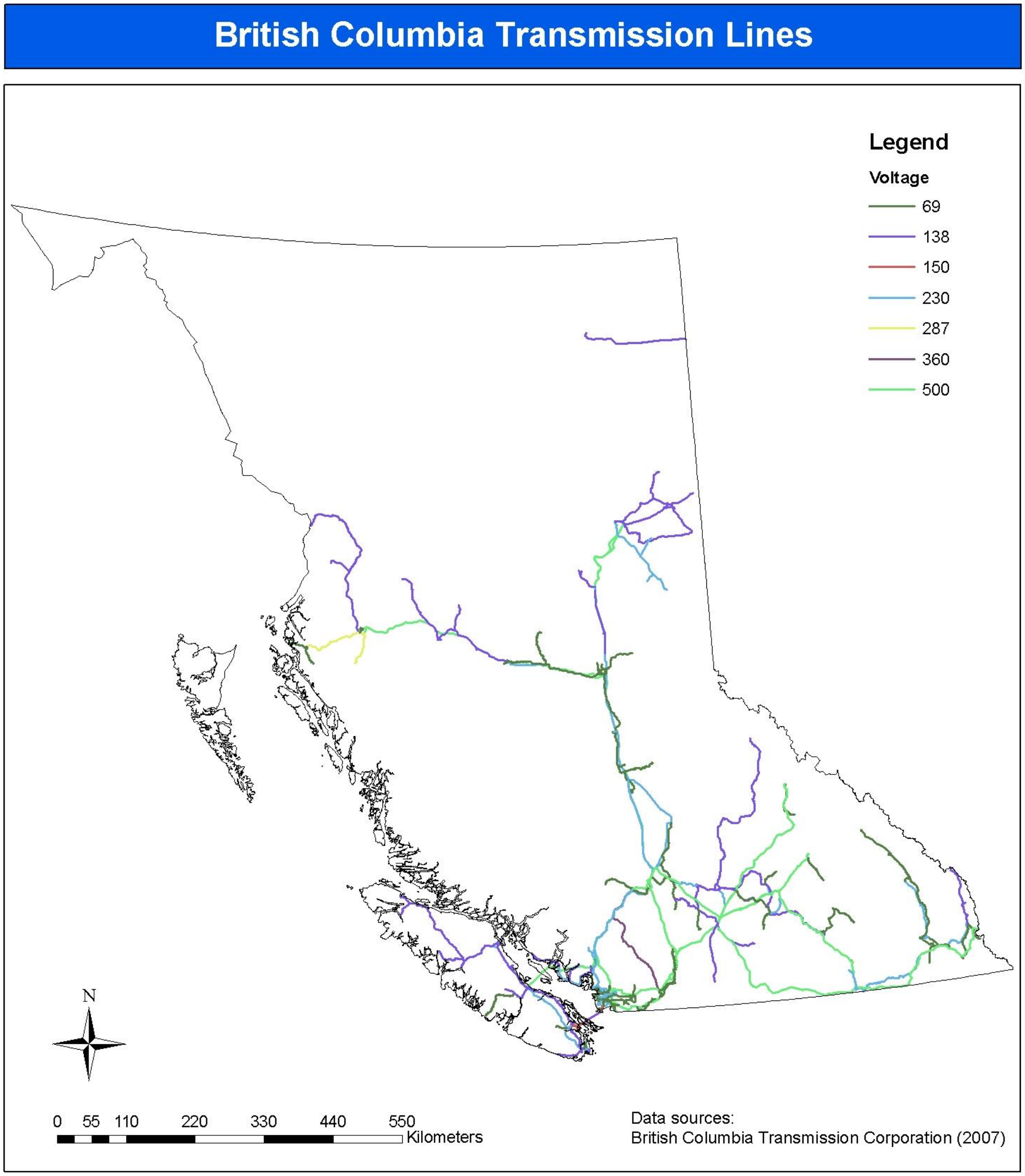

Figure 38: Map of existing transmission lines in BC

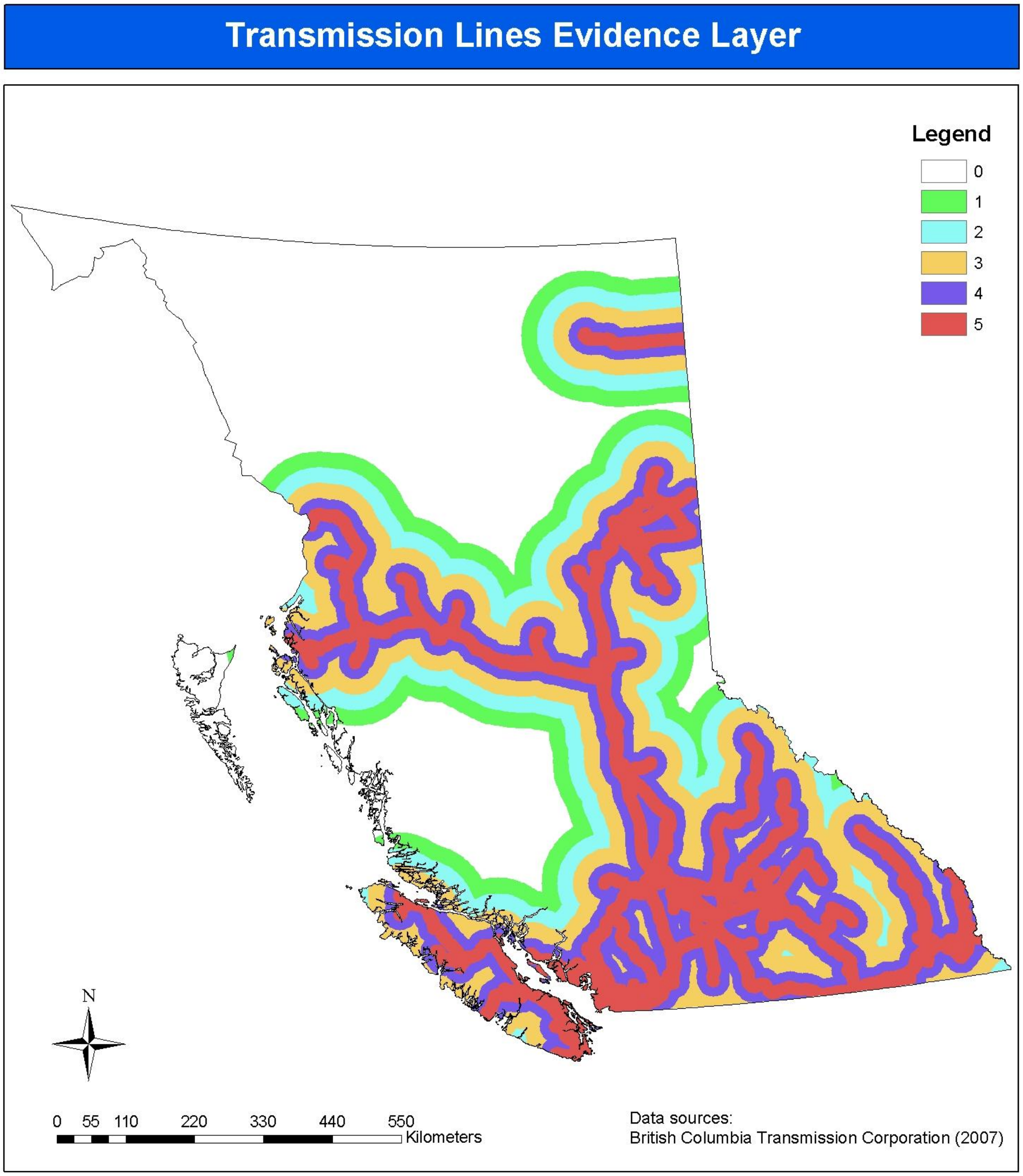

Figure 39: Transmission evidence layer

5.4 Land Use

According to BC MEMPR Titles Division, geothermal land tenure requests cannot include the following land use types:

1. Parks, protected areas, conservancies, recreation areas, ecological reserves;
2. Located within the Muskwa-Kechika Management Area;
3. Federal lands including Indian Reserves;
4. Areas with existing geothermal or petroleum and natural gas tenure (pending development of policy regarding potential future geothermal dispositions within these areas).

These land use types are combined into Figure 40 and can be subtracted from the final favourability map.

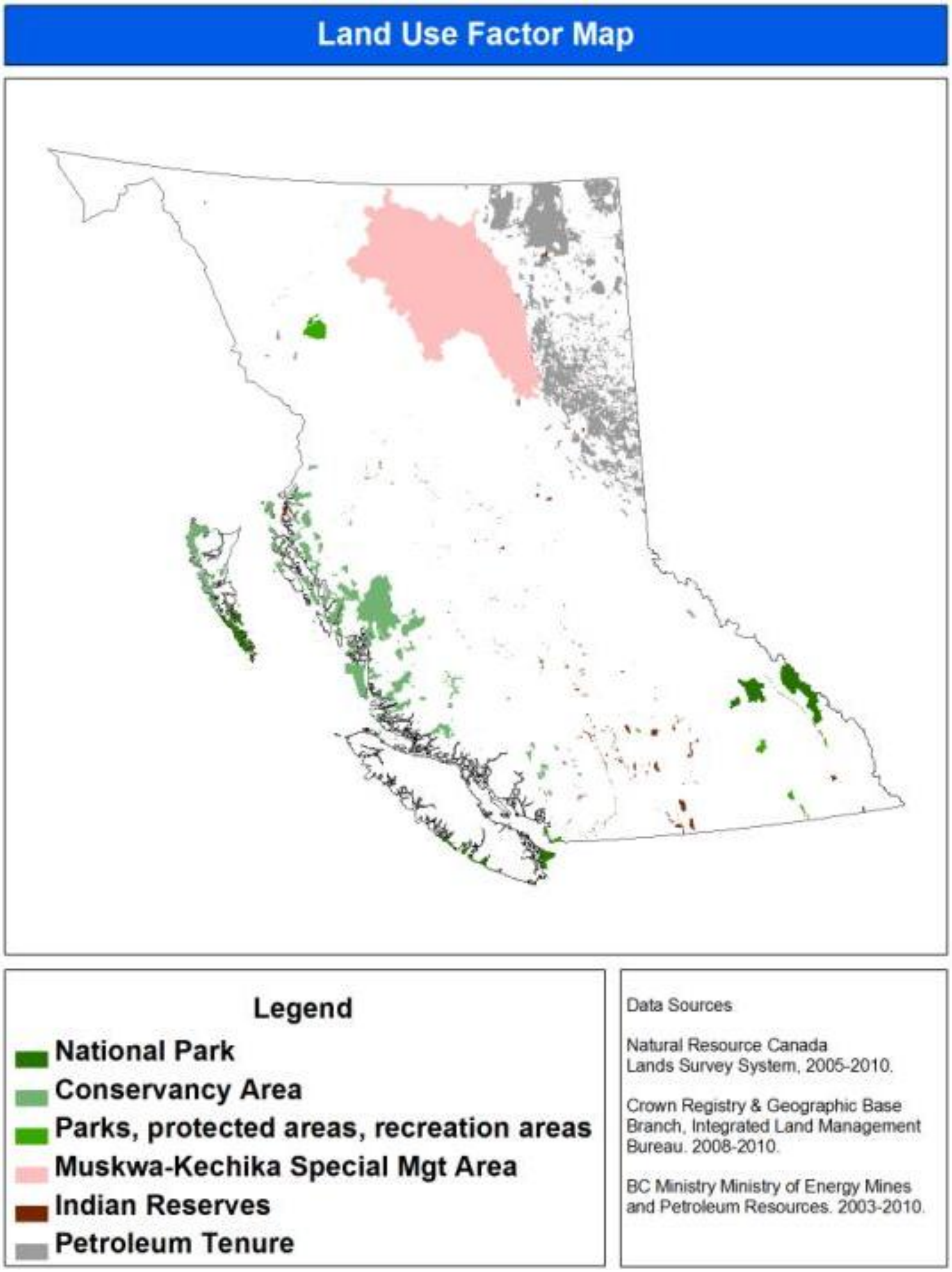

Figure 40: Map of areas precluded from geothermal tenure, including: provincial and national parks, conservancies, federal land, Indian reserves, existing oil and gas tenures, and special management areas

6 Results

The 10 evidence layers generated were combined into a series of factor maps which ultimately make-up the final geothermal favourability map. The temperature and permeability factor maps were combined to form a complete geothermal resource factor map (see Figure 41). This map was then integrated with the market & infrastructure factor map; the land use factor map showing areas in-eligible for geothermal tenure is also combined with the geothermal favourability map if desired.

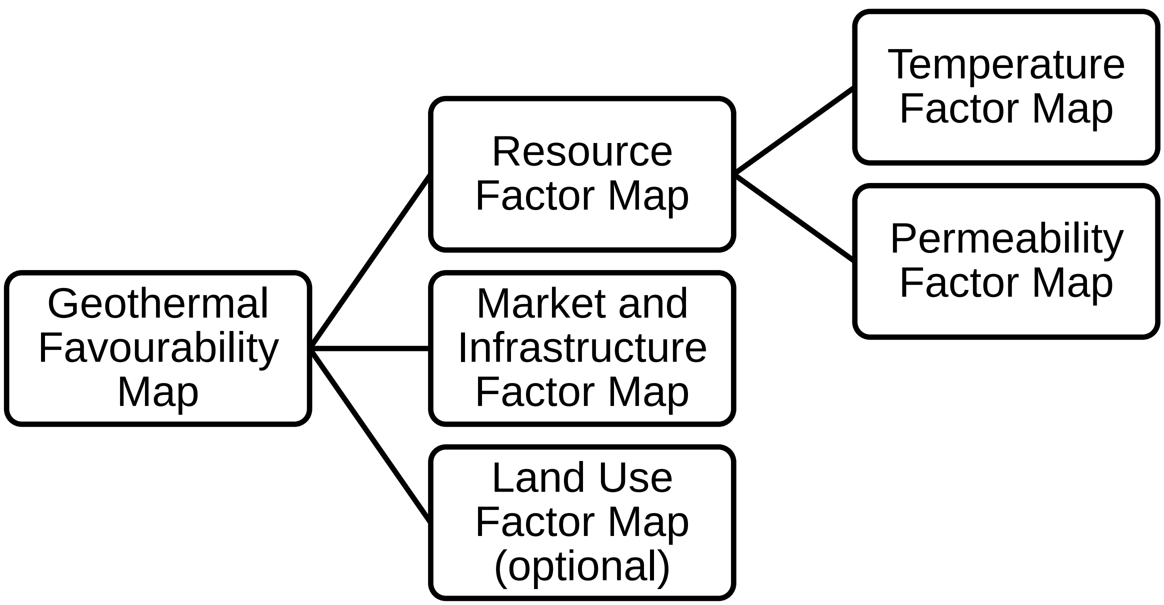

Figure 41: Factor maps comprised in the geothermal favourabiltiy map

Each evidence layer and output factor map were normalized using a scale from 1-5. A consistent raster grid covering the province (plus a 25-100 km buffer to account for relevant data points outside of the provincial boundaries) was used throughout the analysis, and all layers were discretized into a grid with a cell size of 1km by 1km.

Weighted overlay, weighted summation and the Analytical Hierarchy Process (AHP) methodologies were applied to assign weights to each evidence layer and compile the maps in ArcGIS. Both weighted summation and AHP methodologies were employed in detail to produce the full set of maps in this work. Evidence layers were assigned weights based on their importance to geothermal favourability; the layers were combined and re-classified resulting in output factor maps that identify favourable areas for each factor group (i.e. temperature, permeability, resource, and market & infrastructure).

For weighted summation, weights were selected subjectively, based on the author's judgment of the importance of each evidence layer. Benefits of the weighted summation or weighted overlay tools were the flexibility in assigning weights, the ability to use floating point values in raster cells, and their availability as standard tool in ArcGIS 9.3.

The second method for assigning weights was the AHP which is discussed in detail in Section 6.1. Weights in the AHP were calculated from a pair-wise comparison matrix where the importance of each evidence layer compared to another was judged by the author. The AHP was particularly useful when considering multiple (>2) criteria/evidence layers. The AHP process was more structured, and included a check for consistency. Some drawbacks of the methodology were that the AHP script had to be downloaded from the ESRI website and was only compatible with certain versions of Windows, and input rasters for the AHP were restricted to integer values.

Overall, the AHP weight selection process was considered to be more robust and was the main method used in this work. Results from the weighted summation process were included for comparison in Appendix D to H.

6.1 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) weighted evaluation method was implemented using a Visual Basic macro developed by Marinoni (2004) for GIS. The Analytical Hierarchy Process is a popular decision-making tool developed by Thomas L. Saaty that assigns weights based on a pair-wise comparison of criteria (Saaty and Vargas, 1991). Decisions are decomposed into a hierarchical structure such that multiple criteria are analyzed for a specific objective (Figure 42).

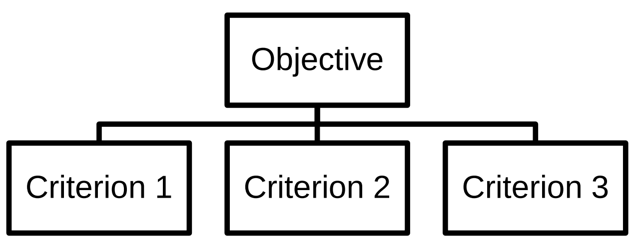

Figure 42: Hierarchy

To determine the weights of each evidence layer, each criterion (or layer) was compared against each other and a judgment on the relative importance of each layer was made and an appropriate score from 1 to 9 was assigned (Table 16). Pair-wise comparison greatly reduces the conceptual complexity by comparing only two criteria at a time (Boroushaki et al., 2008). The pair-wise comparison is performed in a square preference matrix from which eigenvalues and eigenvectors are calculated.

Table 16: Example scale for comparisons (Saaty & Vargas, 1991)

Intensity of importance	Description
1	Equal importance
3	Moderate importance of one factor over another
5	Strong or essential importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values
Reciprocals	Values for inverse comparison

In the temperature factor map, five evidence layers that provided indications of heat were compared. Preference values from 1 to 9 were assigned based on the intensity of importance (Table 17). For example, a judgment that volcanic centers have a moderate importance over hot springs yielded a preference value of 3. The reciprocal value of 0.333 was automatically calculated for the comparison of hot spring importance relative to volcanic centers. The most direct indicators such as temperature gradient and heat flow (combined into a single temperature evidence layer) were assigned the highest intensity of importance values. Volcanic centers provide evidence of a heat source and were given medium influence value. Hot springs are evidence of the presence of anomalous heat, however the source of the anomalous heat does not necessarily guarantee there is a commercial resource at depth, and they were given a lower influence value. Geothermometry from hot springs provides more information about the resource temperature at depth; however the estimates require several assumptions, reducing the confidence in the data, and were given lower weight. Geology was deemed to have low to moderate importance for resource favourability. Since there is no preference for layers when compared to the same layer, the preference values in the main diagonal of the matrix were always equal to 1.

Table 17: Preference matrix for the temperature factor map

	Volcanic centers	Geothermo-metry	Hot springs	Temperature	Geology
Volcanic centers	1	2	3	0.5	3
Geothermom-etry	0.5	1	2	1	3
Hot springs	0.3333	0.5	1	0.3333	2
Temperature	2	1	3	1	3
Geology	0.3333	0.3333	0.5	0.3333	1

The weights assigned to each criterion were calculated following the methodology of Saaty and Vargas (1991):

1. The square preference matrix was used to calculated the eigenvalues of the matrix; the number of eigenvalues calculated was equal to the order of the matrix (e.g. for the temperature preference matrix, there were 5 eigenvalues.
2. The eigenvectors of the largest eigenvalue in step 1 were calculated[11]. The eigenvector had 5 components, equal to the order of the matrix.

[11] For details on computations of eigenvalues and eigenvectors see Davis (2004).

3. The components of the largest eigenvector were summed and each component was divided by this sum to ensure the sum of the weights was 1 (normalization).
4. The value of each component is considered to be the weight. Each criterion (raster layer) is multiplied by the calculated weight and added together.

The eigenvalues and eigenvectors from the AHP tool are included in the Appendix I. Output criteria weights from the temperature preference matrix are shown in Table 18.

Table 18: Criteria weights for 5 evidence layers in the temperature factor map

Layer	Calculated weight
Volcanic Centers	27.63%
Geothermometry	21.73%
Hot Springs	11.03%
Temperature	31.84%
Geology	7.77%
Total	100.00%

To check that the prioritization of alternatives was consistent throughout the pair-wise comparison matrix, a numerical index called the consistency ratio was applied (Equation 6). Consistency ratios above 0.1 should be revised (Saaty & Vargas, 1991). The consistency ratio (CR) is the ratio of the consistency index (CI) to an average consistency index also known as a random index (RI).

Equation 6: Consistency Ratio

$$CR = \frac{CI}{RI}$$

The consistency index was calculated from the preference matrix using Equation 7, where λ_{max} is the largest eigenvalue from the preference matrix, and n is the order of the matrix.

Equation 7: Consistency Index

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

The value of RI was derived from expert knowledge and experience and depends on the number of criteria/the order of the matrix (Table 19). For the temperature factor map (Figure 43), a consistency ratio of 0.0425 was calculated from the matrix output.

Table 19: Values for the random index (RI), modified from Boroushaki (2004) and Saaty (1980)

Number of criteria	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

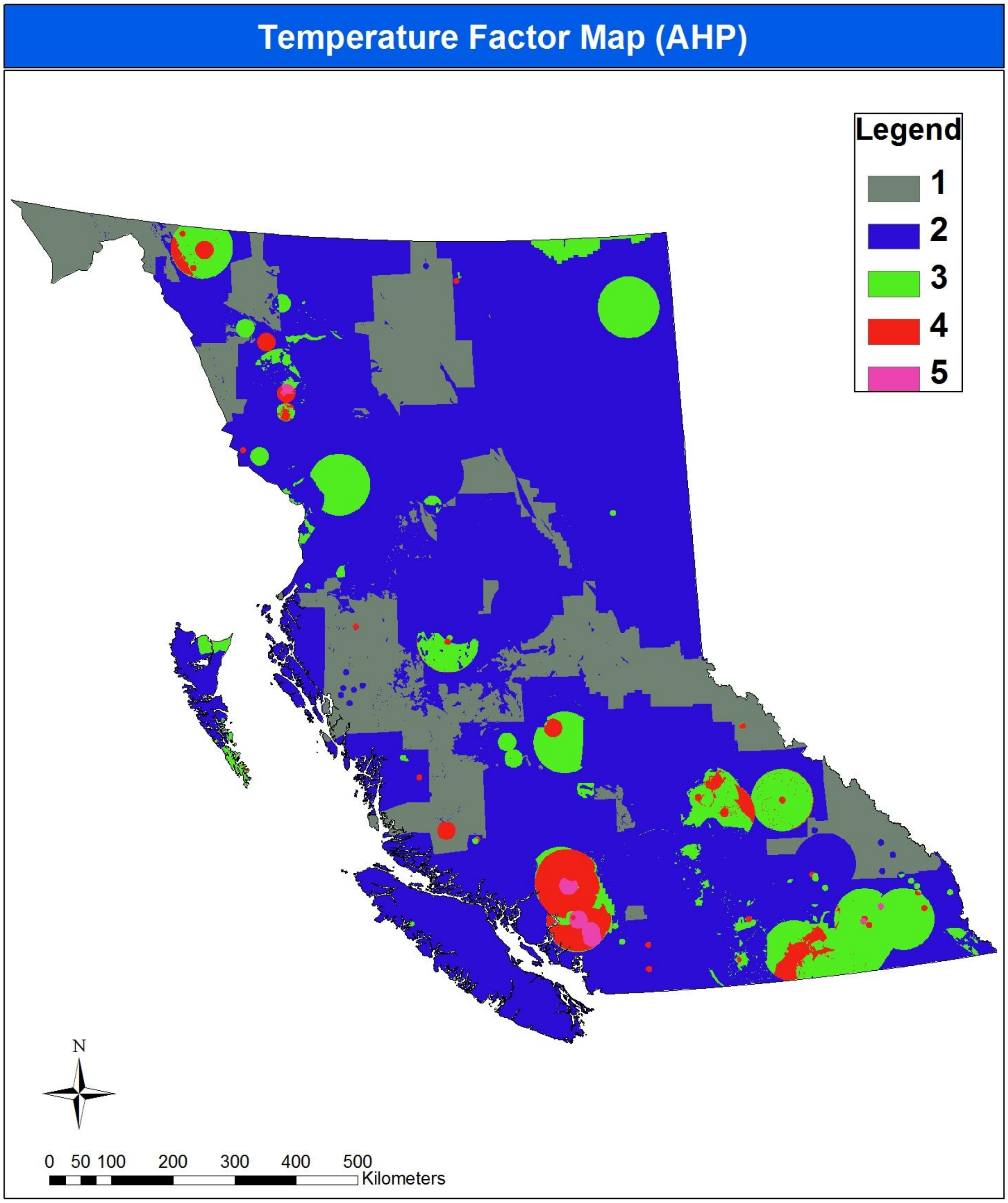

Figure 43: Temperature factor map

6.1.1 Permeability Factor Map

The two evidence layers in the permeability factor map were entered into a preference matrix and intensity of importance values were chosen. A very strong preference for the fault density layer over the earthquakes layer was selected (Table 20). This judgment was supported by results from other geothermal favourability maps (West Java and Nevada), that found generally weaker correlation for earthquakes than other indicators (Carranza, Wibowo, Barritt, & Sumintadireja, 2008) and (Coolbaugh, et al., 2002). The criteria weights are shown in

Table 21; a consistency ratio of zero was obtained (since only two layers were being compared and reciprocal values are automatically calculated). Results for the permeability factor map are shown in Figure 45.

Table 20: Preference matrix from the permeability factor map

	Fault density	Earthquakes
Fault density	1	8
Earthquakes	0.125	1

Table 21: Criteria weights for the permeability factor map

Layer	Calculated weight
Fault density	89.89%
Earthquakes	11.11%
Total	100.00%

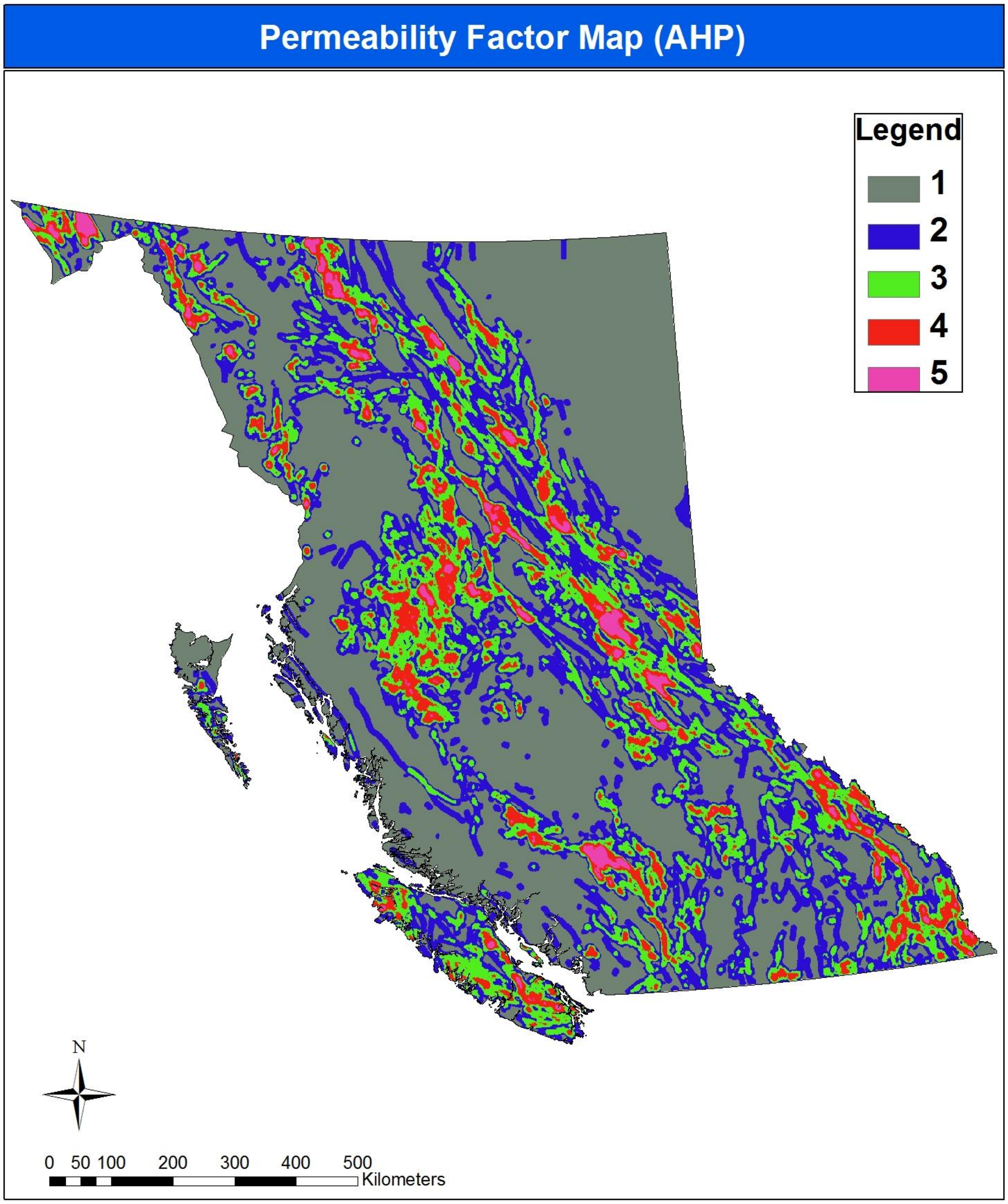

Figure 44: Permeability factor map produced using the AHP for assigning weights

6.1.2 Resource Factor Map

The temperature and permeability factor maps were combined to produce the resource factor map. A strong preference was assigned to the temperature factor map (Table 22) since it is the most important factor for geothermal. And, if EGS technology continues to develop, permeability can be enhanced through hydro-fracturing. The criteria weights derived in the Analytical Hierarchy Process are shown in Table 23 and the resulting resource factor map is shown in Figure 45.

Table 22: Preference matrix for the resource factor map

	Permeability	Temperature
Permeability	1	0.25
Temperature	4	1

Table 23: Criteria weights for the resource factor map

Layer	Calculated weight
Permeability	20.00%
Temperature	80.00%
Total	100.00%

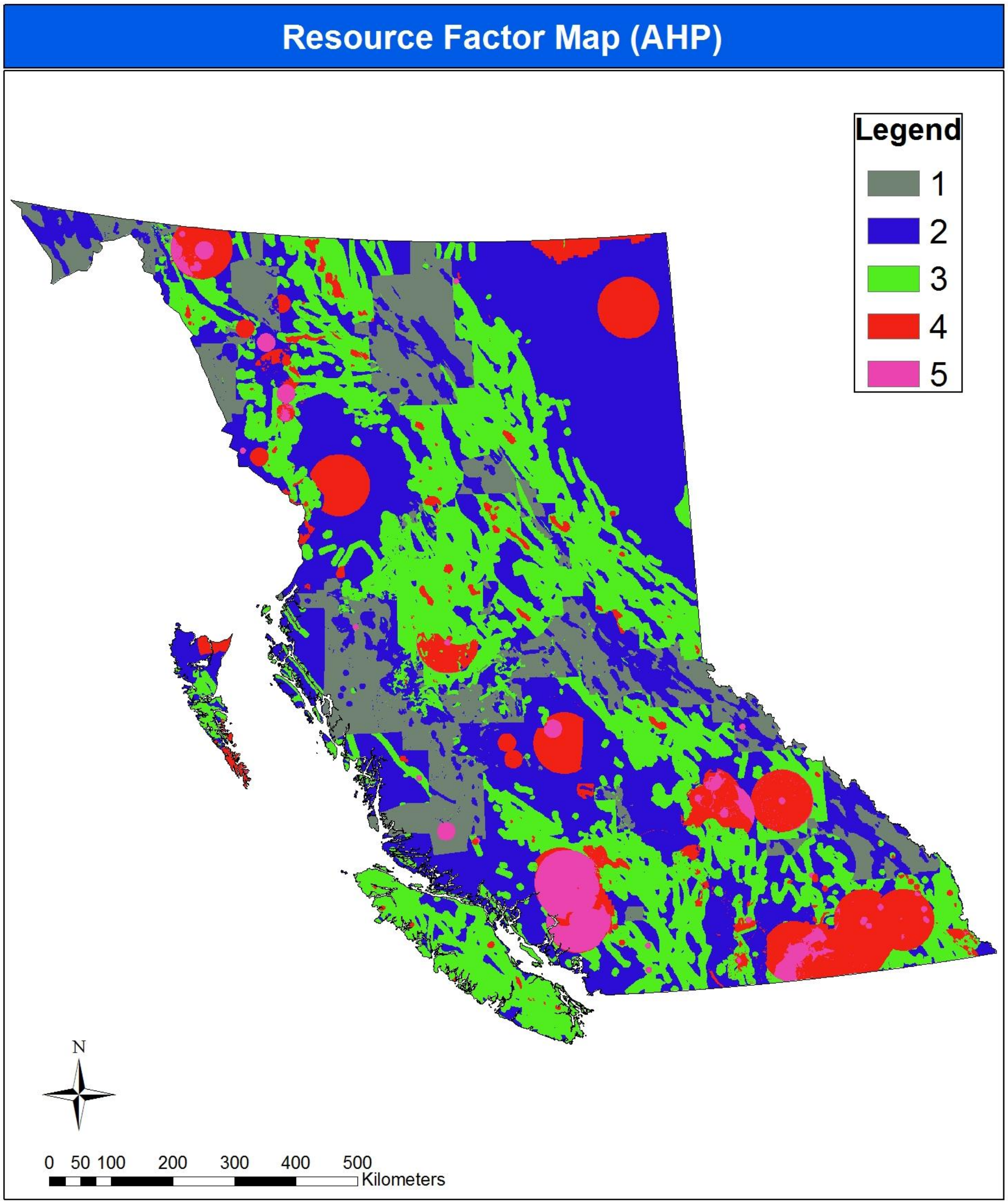

Figure 45: Resource factor map produced using the AHP for assigning weights

6.1.3 Market and Infrastructure Factor Map

Three evidence layers were compared and assigned 'intensity of importance' values in a preference matrix (Table 24: Preference matrix for the market & infrastructure factor map. The weights assigned to each layer are shown in Table 25, with transmission accounting for over three quarters of the total weight. A consistency ratio of 0.0515 was calculated for the matrix. The resulting market & infrastructure factor map is shown in Figure 46: Market & infrastructure factor map produced using

Table 24: Preference matrix for the market & infrastructure factor map

	SOP prices	Population density	Transmission
SOP prices	1	3	0.1667
Population density	0.3333	1	0.1111
Transmission	6	9	1

Table 25: Weights for the market & infrastructure factor map

Layer	Calculated weight
SOP prices	16.18%
Population density	6.79%
Transmission	77.03%
Total	100.00%

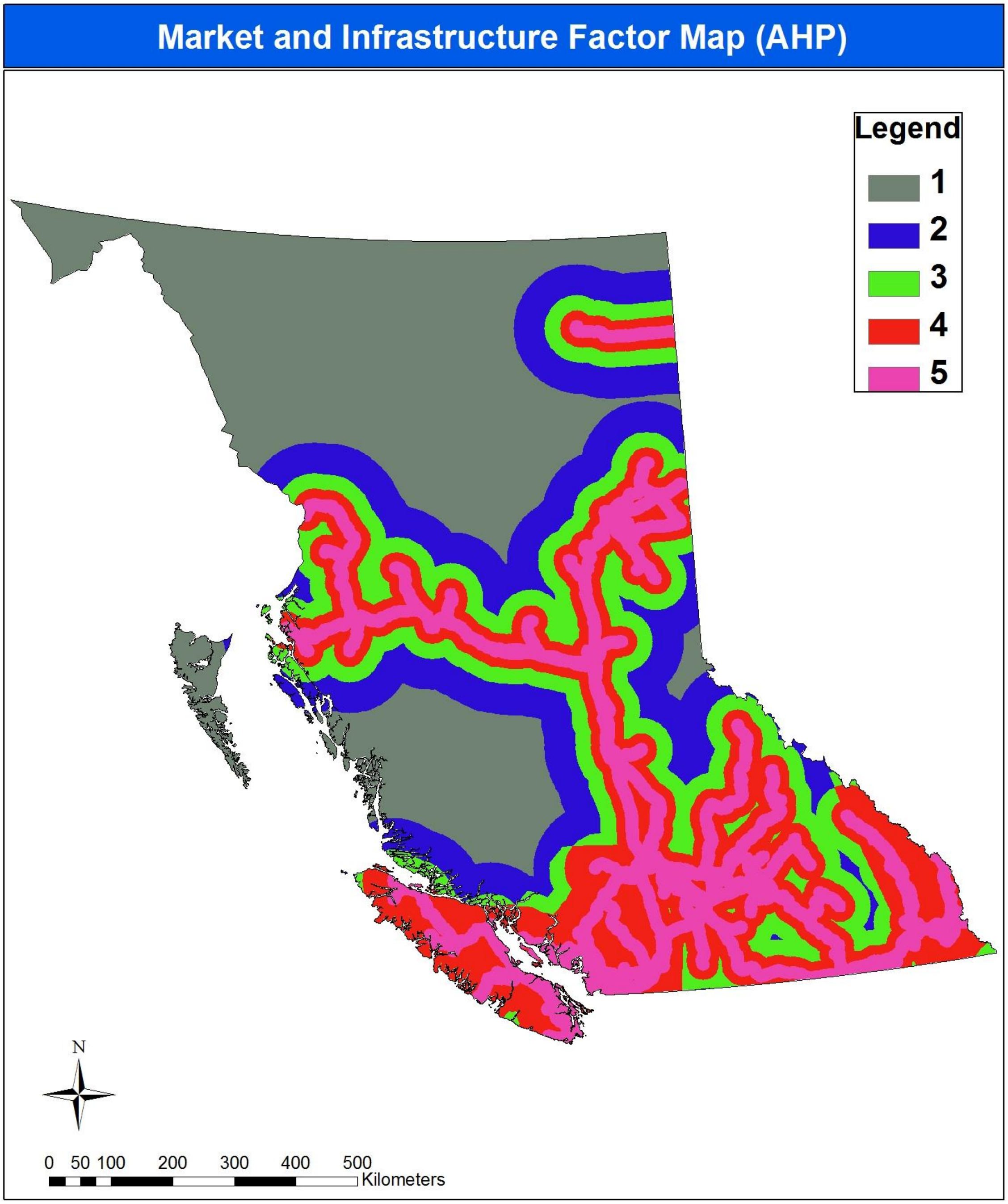

Figure 46: Market & infrastructure factor map produced using AHP for assigning weights

6.1.4 Geothermal Favourability Map

The geothermal favourability map components were compared in a preference matrix (Table 26) to generate weights for the favourability map (Table 27). The resource factor map was deemed more important than the market & infrastructure factor map because without a geothermal resource, the market and infrastructure is irrelevant. The geothermal favourability map of British Columbia is shown in Figure 47: Geothermal favourabiltiy map of British Columbia produced using.

Table 26: Preference matrix for the geothermal favourability map

	Resource	Market & Infrastructure
Resource	1	5
Market & Infrastructure	0.2	1

Table 27: Weights assigned to the factor maps to produce the geothermal favourability map

Factor map	Calculated weight
Resource	83.33%
Market & Infrastructure	16.67%
Total	100.00%

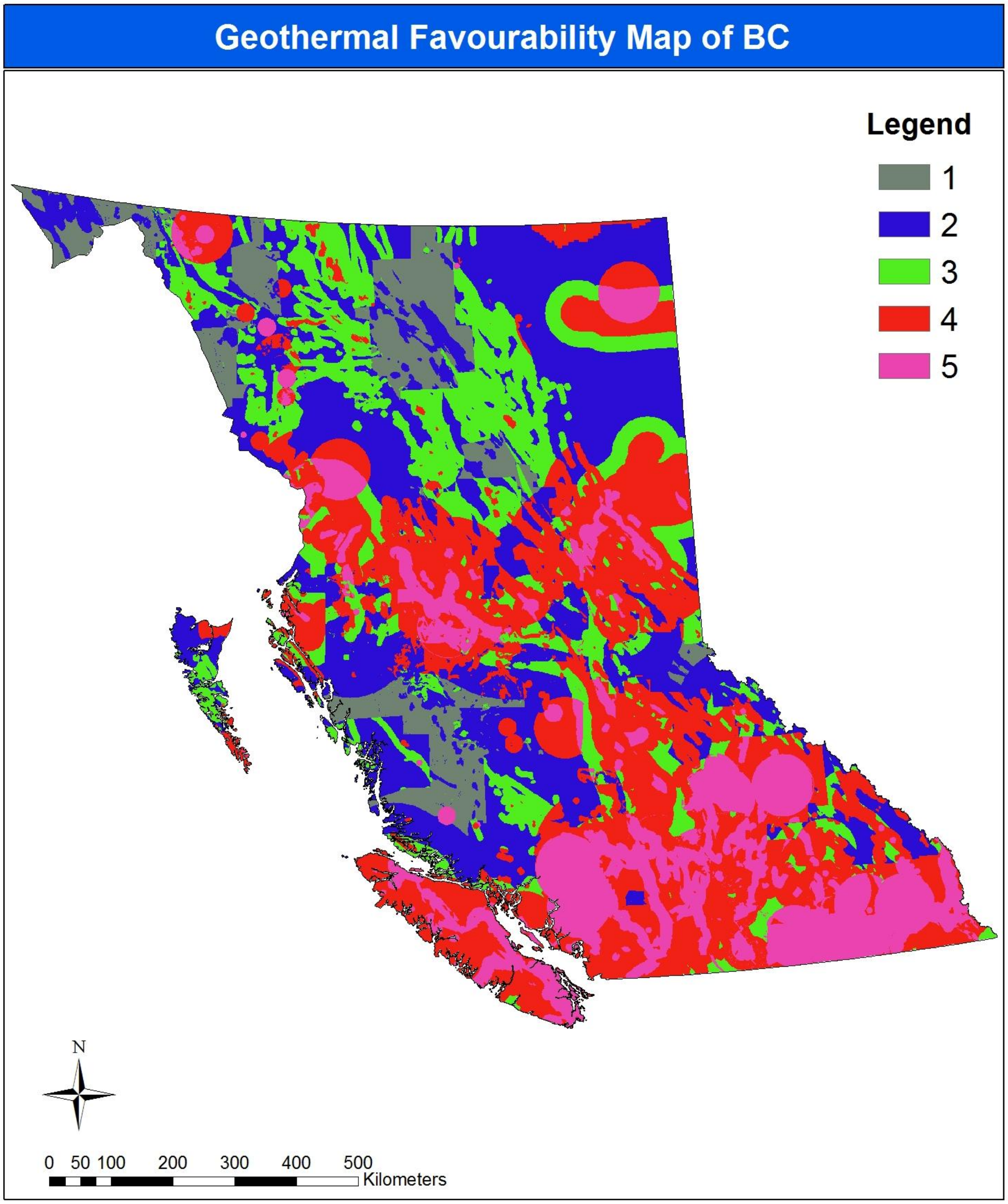

Figure 47: Geothermal favourabiltiy map of British Columbia produced using AHP for assigning weights

7 Discussion

7.1 Data Quality and Model Validation

This work relies on secondary, non-random data which introduces measurement uncertainty into the model. For example, the thermistor accuracy for the temperature log measurements used to calculate the temperature gradient was 0.01K (Jessop, et al., 2005).

There was uncertainty in the calculated temperatures from the geothermometry evidence layer. A numerical modeling study examining the potential effects of mixing and re-equilibration by (Ferguson, Grasby, & Hindle, 2009) reveals that silica-based geothermometers may underestimate reservoir temperature by 10 to 35% for fault-controlled (tectonic) hot springs in Canada. The under-estimation of resource temperatures by geothermometry has also been noted for samples from Mount Meager (Souther, Open-File Report 85-521, 1985), (Nevin Sadlier-Brown Goodbrand Ltd., 1974), and (Ghomshei & Clark, 1993). Much of BC experiences significant levels of annual precipitation which may suppress hot springs and lead to mixing with cold waters creating a 'rain curtain' effect experienced in much of the Cascade volcanic range. Heavy precipitation masks or reduces geothermal signatures, particularly for geochemical and geophysical exploration tools. Some of this uncertainty is reduced by assigning large temperature ranges to each class in the geothermometry scoring table (Table 7), and assigning lower temperature ranges for the silica-based geothermometer.

Other possible sources of uncertainty in the analysis were transformation error and human error. Each evidence layer was classified from 1 to 5 based on past experience from geothermal occurrences around the world, rules of thumb, and the current state of geothermal technology. The normalization of each evidence layer from 1 to 5 helps to reduce the level of uncertainty in the data.

Once evidence layers were combined into factor maps, the factor maps were transformed using the natural breaks function in ArcGIS to maintain 5 classes. This step contributes the greatest uncertainty in transforming the data. Cells with no data in each evidence layer were assigned a value of 0 to facilitate the combination of multiple rasters. Thus some areas with less data available may receive low scores, while other areas with multiple lines of evidence receive higher scores.

The selection of weights by a single person introduces a certain bias to the maps. Different stakeholders such as geologists, engineers, developers, community members, utilities, environmentalists, investors, and government regulators would assign weights in a different manner. To reduce bias in the maps, one could incorporate the weights of multiple parties with diverse backgrounds and use the average value for the final map. Also, a sensitivity analysis could be done to determine the effect of changing different model parameters.

The labelling of numeric values (scores from 1 to 5) with descriptive language for geothermal potential or favourability contributes additional uncertainty in the interpretation of the values. To facilitate comparison, scores were assigned linguistic terms (Table 28).

Table 28: Linguistic terms associated with map scores

Score	Favourability
1	Low
2	Low to Moderate
3	Moderate
4	Moderate to High
5	High

Model calibration and validation are important steps in every analysis and provide credibility to the model results. This work was not meant to be used as a predictive model of geothermal occurrences, but to identify areas where more-focused regional- and project- scale exploration should be carried out.

As a qualitative validation, model outputs are in general agreement with previous mapping exercises and studies (e.g. Fairbank & Faulkner, 1992 and BC Hydro, 2002). The most advanced geothermal project to date in the province, Mount Meager (with confirmed commercial grade temperatures) was classified as having high potential in the model providing further validation. The ultimate test for the model will be when geothermal power plants come on line. Given the intended use of the maps, the scale and resolution of the data, the uncertainty introduced is unlikely to impact model results.

7.1.1 Resource Map Comparison

In the 1992 geothermal resource of British Columbia map shown in Figure 48, Fairbank et al. (1992) identified areas of moderate and high geothermal potential based on the following characteristics of the geothermal environment: deep-seated faults, deep sedimentary basins, radiogenic plutons, late Tertiary to recent volcanic complexes and flows, and hot springs. Areas of moderate potential contain some of these characteristics and areas of high potential contain multiple characteristics. The 1992 map provided a useful comparison for the resource maps produced in this work (Figure 45 for AHP and Appendix F for Weighted Summation). All maps cover the same area discretized into 951,397 cells measuring 1km by 1km. A raster of the 1992 resource map was generated by assigning a score of 3 to areas of moderate potential, and a score of 5 to areas of high potential; areas that were un-classified in the 1992 resource map were assigned a score of 1 to facilitate mathematical operations with other rasters.

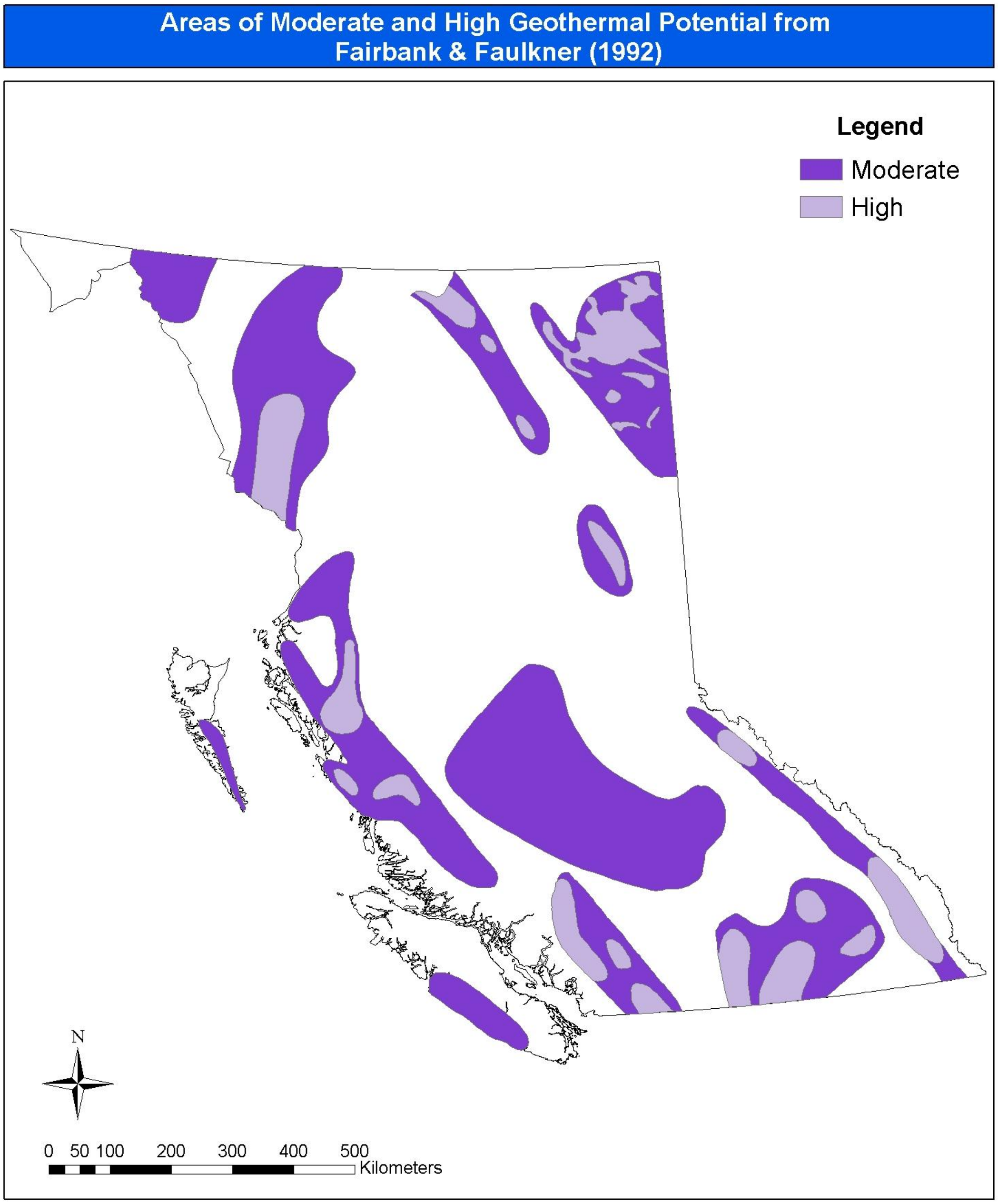

Figure 48: 1992 geothermal resource of British Columbia map showing areas of moderate and high potential (modified from Fairbank & Faulkner, 1992)

To compare the differences between the maps, the 1992 resource map was subtracted from the resource factor map to produce Figure 49. In this Figure, raster values ranged from -4 to 4, with values >±2 showing areas of significant difference. Blue demarcates the areas highlighted in the 1992 resource map and not in the resource map while red shows areas not included in the 1992 map. Specific areas (shown with the corresponding letter in Figure 49) include:

A. Lakelse Lake & Gardner Canal Area: postulated to have a plutonic heat source by Fairbank & Faulkner (1992) was not highlighted in the resource factor map because of the low weight (~8% in the temperature factor map) applied to the geology evidence layer (which contains data on intrusive rocks). The resource factor map did show Lakelse hot springs as favourable; however the buffer did not extend as far as the 1992 interpretation.
B. Valemount & Southern Rocky Mountain Trench: these areas had larger buffers around favourable area in the 1992 map than in the resource factor map. Both areas were not associated with major volcanic features.
C. Northeast B.C. thermal anomaly: the areas of high potential were defined by temperature gradient contours in the 1992 map, a level of detail that was not used in the resource factor map. The center of the anomaly however was captured in the resource factor map (see white dot in Figure 49).
D. Near Iskut-Unuk River cones, Clearwater volcanic field, and the Kootenay's: these areas were highlighted as favourable by the resource factor map, primarily due to borehole measurements of heat flux $\geq 90 mW/m^2$ and the 25 km buffer that was assigned to the data points.
E. Garibaldi Volcanic Belt: this area showed red, crescent shapes from the buffered area surrounding volcanic centers in the belt. The buffered area was larger than the 1992 polygon.

The differences listed here suggest that the resource factor map elucidates volcanic related resources and areas with anomalous borehole measurements of heat flow and/or temperature gradient.

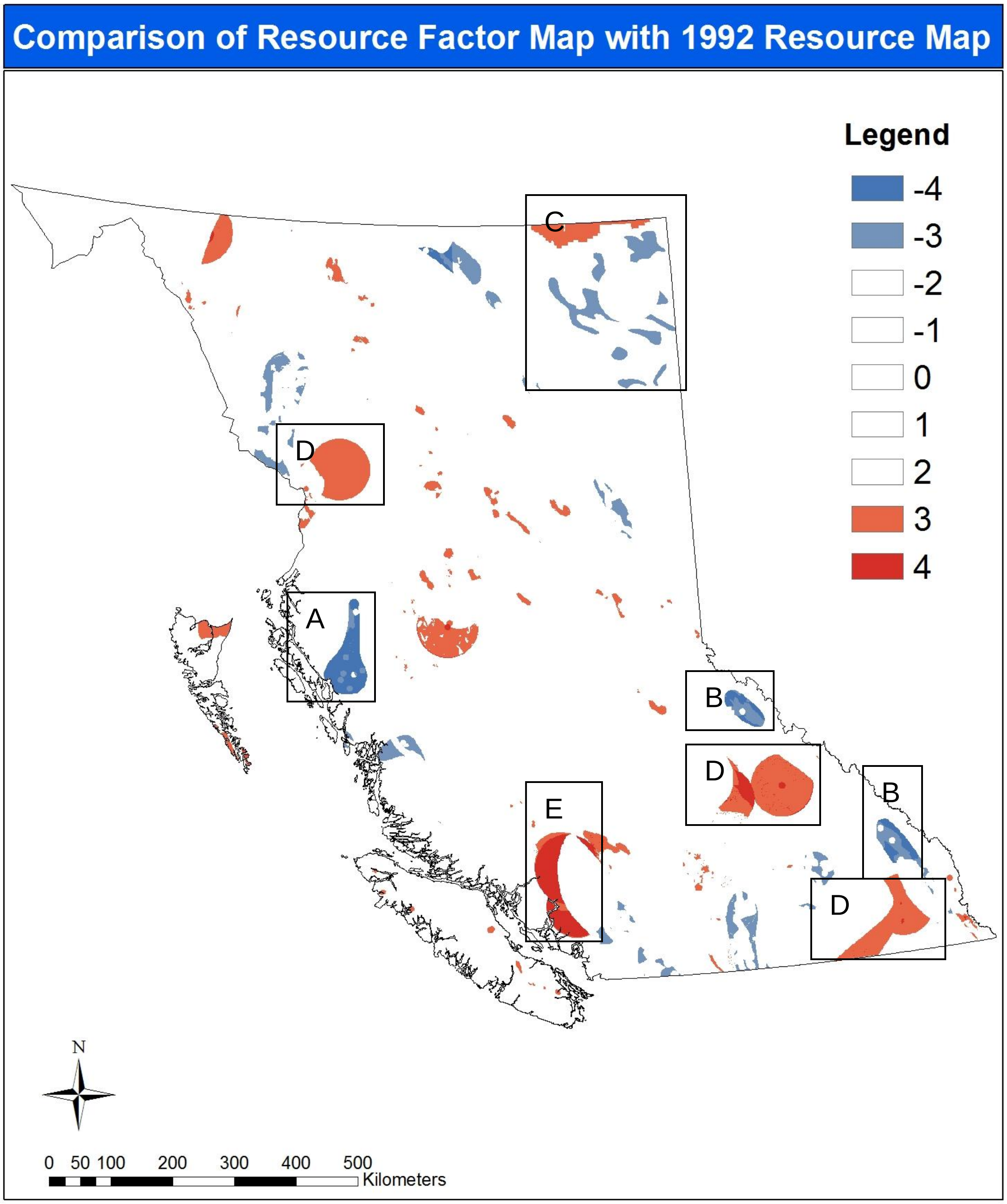

Figure 49: Comparison of the resource factor map with the 1992 resource map generated by subtracting the 1992 resource map from the resource factor map raster.

7.1.2 Influence of Market & Infrastructure on the Favourability Map

Previous favourability maps have not incorporated market and infrastructure factors into the analysis, preferring to keep these factors separate, from resource indicators. However, these factors are crucial in determining whether or not a geothermal project is economically feasible and should be included in the favourability analysis. As a standalone map, the market and infrastructure factor maps are applicable to all types of power generation, not just geothermal and may prove useful to other alternative energy concepts in BC.

The favourability map was compared with the resource factor map which provided a baseline for comparison (since market and infrastructure factors were not considered). By incorporating market and infrastructure factors into the analysis, a larger area was classified as 4 or 5 (moderate or high favourability). The different scoring distribution for the maps is shown in

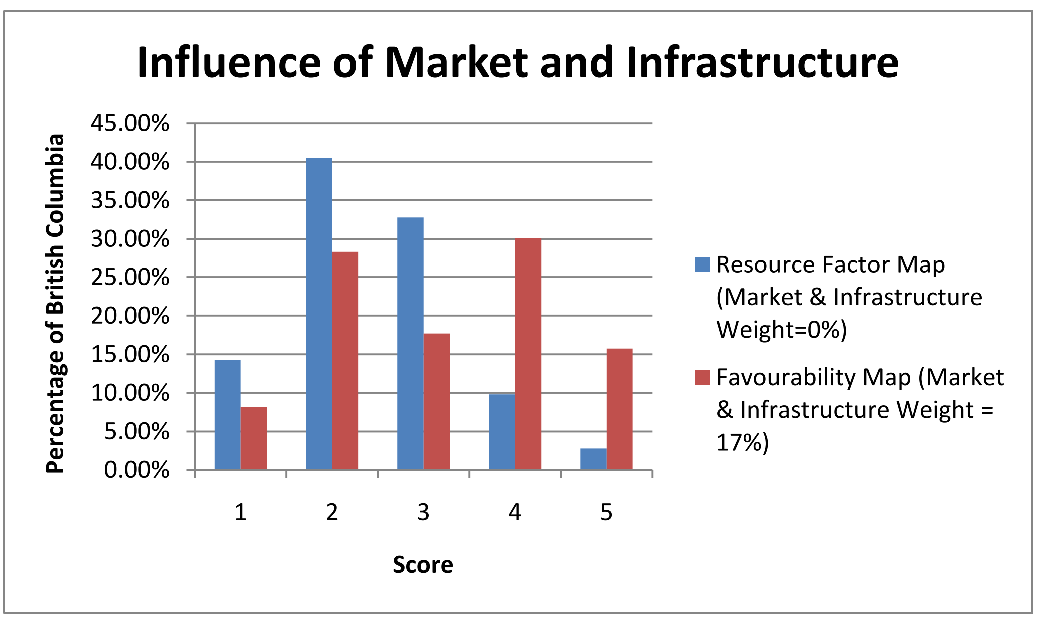

Figure 50. As expected, the increase in scores was observed along transmission corridors and areas with high population density and higher prices.

The results suggest that if favourable market and infrastructure conditions exist, marginal geothermal project become viable and receive higher favourability scores.

The construction of the Northwest Transmission Line to northwest BC and other new transmission lines will shift the infrastructure factors to become more favourable in the area requiring the map to be updated.

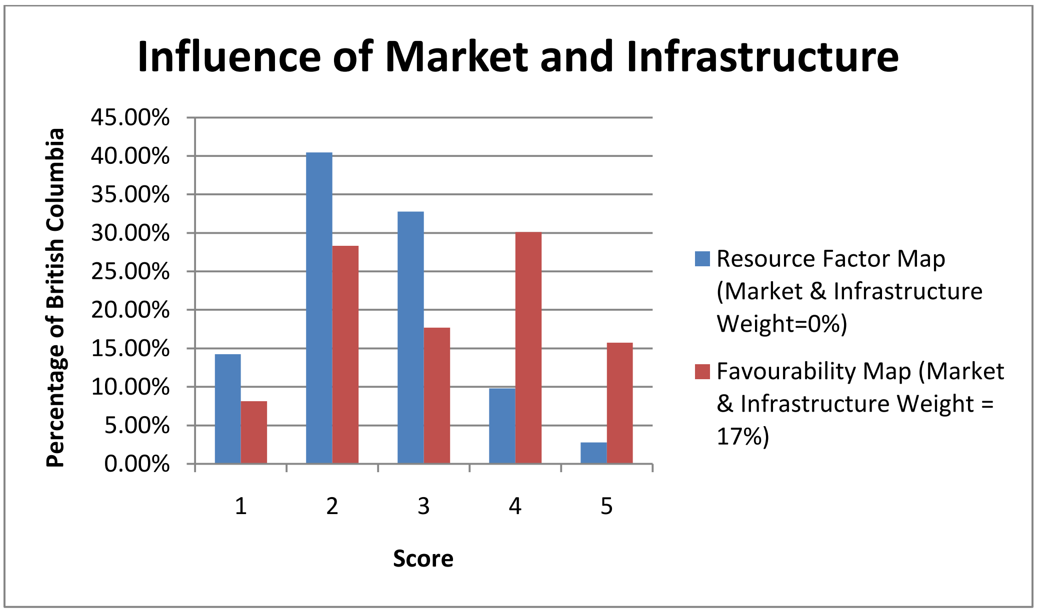

Figure 50: Chart comparing the distribution of scores using different weights for the resource factor map

7.2 Additional Exploration Techniques

There are several additional exploration techniques for geothermal that are not included as evidence layers in the resource factor map. These techniques were not applied if there was insufficient data, poor data coverage, beyond the scope of the current work, or if technique was still under development. Remote sensing, geophysics, and GPS techniques are discussed briefly in the following section as potential future tools that could be applied to help delineate BC geothermal resources.

7.2.1 Remote Sensing

Airborne and space-borne remote sensing techniques can be useful in identifying geothermal features such as geothermal indicator minerals, thermal anomalies, buried faults, changes in ground surface, and stressed vegetation. These tools have been tested at sites in Nevada with known geothermal activity (Nash, Johnson, & Johnson, 2004), (Kratt, Calvin, & Coolbaugh, 2006), (Coolbaugh, Kratt, Fallarcaro, Calvin, & Taranik, 2006) and are now being tested for their predictive capabilities in geothermal exploration.

In BC, the image analysis toolbox available through the Map Place website hosts several ASTER images free for download. The images are both day and night, and taken at different times and during different seasons, thus corrections for thermal inertia and albedo cannot be applied. Steep alpine terrain and tree canopy in BC may cover ground features in the ASTER images a major contrast to the western U.S. desert where these techniques have been tested. Reported investigation of geothermal areas in BC utilizing ASTER images identified mainly large, dark-colored cliffs or areas of clear-cutting by forestry (pers. comm. R. Yehia). The thermal imaging technique with the existing ASTER images is not suitable for inclusion in the BC geothermal favourability map at this stage; this technique may prove useful in the future although the 30 m cell size of ASTER images is likely too large to identify smaller features such as hot springs.

Other remote sensing techniques (not applied here) that may be useful for future exploration include fault mapping and ground motion. Concealed faults or extensions of mapped surface faults, and lineaments can be detected using remote sensing tools. For example, the favourability map of West Java, Indonesia used data from the Shuttle Radar Topography Mission (SRTM) to identify regional-scale faults which generally matched or were extensions of mapped surface faults (Carranza, Wibowo, Barritt, & Sumintadireja, 2008).

Younger faults are more likely to be active and permeable (Blewitt, Coolbaugh, Holt, & Kreemer, 2002) and are the target of geothermal exploration programs. Techniques using Interferometric Synthetic Aperture Radar (InSAR), and Light Detection and Ranging (LIDAR) are being developed to identify these faults and may prove to be useful for local exploration in BC in the future.

7.2.2 Geophysics

Geophysical techniques utilize the physical properties of rock (density, magnetic susceptibility, resistivity, chargeability, elastic properties, and radioactivity) to create a conceptual model of the subsurface geology. A wide variety of geophysical techniques have been used for geothermal exploration to reveal variations in physical properties of rocks caused by the presence of hot and saline fluids (Barbier, 2002). These geophysical techniques include seismic, gravity, magnetics, electromagnetics, self-potential, radiometrics, and thermal measurements.

Provincial scale images for gravity, aeromagnetics, Landsat and Digital Elevation Model (DEM) shaded relief are available from BC MEMPR through MapPlace. National databases include regional geophysics (aeromagnetics, gravity and electromagnetics) are available through the Geological Survey of Canada. Many of the available downloads have large gaps in the data since the original purposes of the data were for different applications. The lack of complete coverage and need for site specific interpretation of geophysical data makes these techniques more suitable for regional exploration.

7.3 External Factors

Political and economic events can have an impact on a geothermal project that is more profound than exploration success (Nevin, 1992). To facilitate the integration of geothermal energy into the BC energy mix, political and economic factors must change. There are several challenges in British Columbia hindering development of geothermal resources. In the current system, Independent Power Producers (IPPs) sell their power to BC Hydro exclusively, creating a monopoly. Uncertainty in the power acquisition process (i.e., when a power call will be issued, if the project will be selected, and what price will be paid) increases the development risk of an IPP project. Renewable Portfolio Standards (RPS) and Feed-In-Tariffs (FITs) in other countries are driving demand for geothermal energy; however these tools are not currently being used in BC but are expected to be introduced as part of the Clean Energy Act (Green Energy Task Force, 2010). Unfortunately, the proposed FIT scheme (BC MEMPR, 2010b) limits projects to a 5 MW capacity which is far too small for geothermal power projects that are typically 50 to 100 MW in size. Programs similar to the production tax credits and investment tax credits (U.S.A.)[12] would be beneficial in providing financial incentives to attract geothermal developers to the province.

BC has enjoyed some of the lowest electricity prices in North America, primarily due to large hydro heritage assets. New run-of-river and wind capacity coming online is at a higher price; from $95.0 to 156.0/MWh (BC Hydro, 2010) however the competitive acquisition process means the lowest cost producers will be selected (assuming an acceptable level of project risk). On a levelized energy cost basis, geothermal continues to be extremely competitive with other sources of generation, and the current prices paid by BC Hydro are likely sufficient for the financial viability of a geothermal project.

The Canadian constitution requires project developers and government to consult and accommodate First Nations when pursuing resource development in their traditional territory. This adds complexity, costs and time for consultations during the land tenure and project development process. Coupled with a lack of government resources to process land tenure nominations and the general

[12] Businesses in the U.S. that place facilities in service that produce electricity from renewable resources after Dec 31, 2008 can choose either the energy investment tax credit, which generally provides a 30 percent tax credit for investments in energy projects or the production tax credit, which can provide a credit of up to 2.1 cents per kilowatt-hour for electricity produced from renewable sources (http://www.geo-energy.org/TaxIncentives.aspx).

unfamiliarity with geothermal energy among the government regulators and the public has led to a decrease in the number of successful geothermal leases in BC.

Geothermal resources are geographically located near volcanoes and areas of active tectonics. In BC, the steep alpine terrain makes access to prospective sites difficult and expensive. An example of this is the recent (August 2010) landslide at Mount Meager which washed out the access road to the geothermal project (Canadian Press, 2010).

Many of the world's geothermal resources remain untapped. For geothermal development companies, countries with a better inventory and understanding of their geothermal resources, better government support, and attractive financial incentives are more likely to be selected for investment.

7.4 Recommendations

To facilitate development of geothermal resources in British Columbia, the following recommendations are made:

1. A catalogue of geothermal data should be made available via a web-based platform similar to (or as an extension of) BC MEMPR's MapPlace website (www.mapplace.ca). The catalogue should include data sets included in this work, as well as additional data from other sources (e.g. oil and gas wells, water wells).

2. Additional exploration and data collection in areas identified as favourable is recommended. Regional-scale work could be conducted by the provincial geological survey to increase the understanding of the nature of the resource, and spur industry interest.

3. Continued application of GIS to geothermal for database management, exploration, and development is recommended. Advanced modeling could include: linking the geothermal map to a cost model to comparatively evaluate different sites, and local analysis for selecting a project site or well locations.

8 Conclusion

This work has identified several favourable areas for further geothermal exploration and development in British Columbia. The resource factor map contains additional data made available since the publication of the 1992 resource map and also includes additional data sets (e.g. earthquake epicentres). The new maps integrate knowledge about the spatial correlation of geologic features and geothermal resources from other countries. This knowledge was applied in GIS in selecting buffer distances around features and in the analytical hierarchy process used for assigning weights to each evidence layer.

The favourability map of BC is the first geothermal map to incorporate market and infrastructure factors which are key factors in project feasibility. Future favourability maps should include these factors as they are extremely important for the economic feasibility of a geothermal project.

The current method of power acquisition and other economic and political factors play a major role in geothermal development or lack thereof in the province. The export goals of the Clean Energy Act are an opportunity for geothermal markets to develop in BC. In order to harness this potential and contribute to BC's low carbon economy, government support is required.

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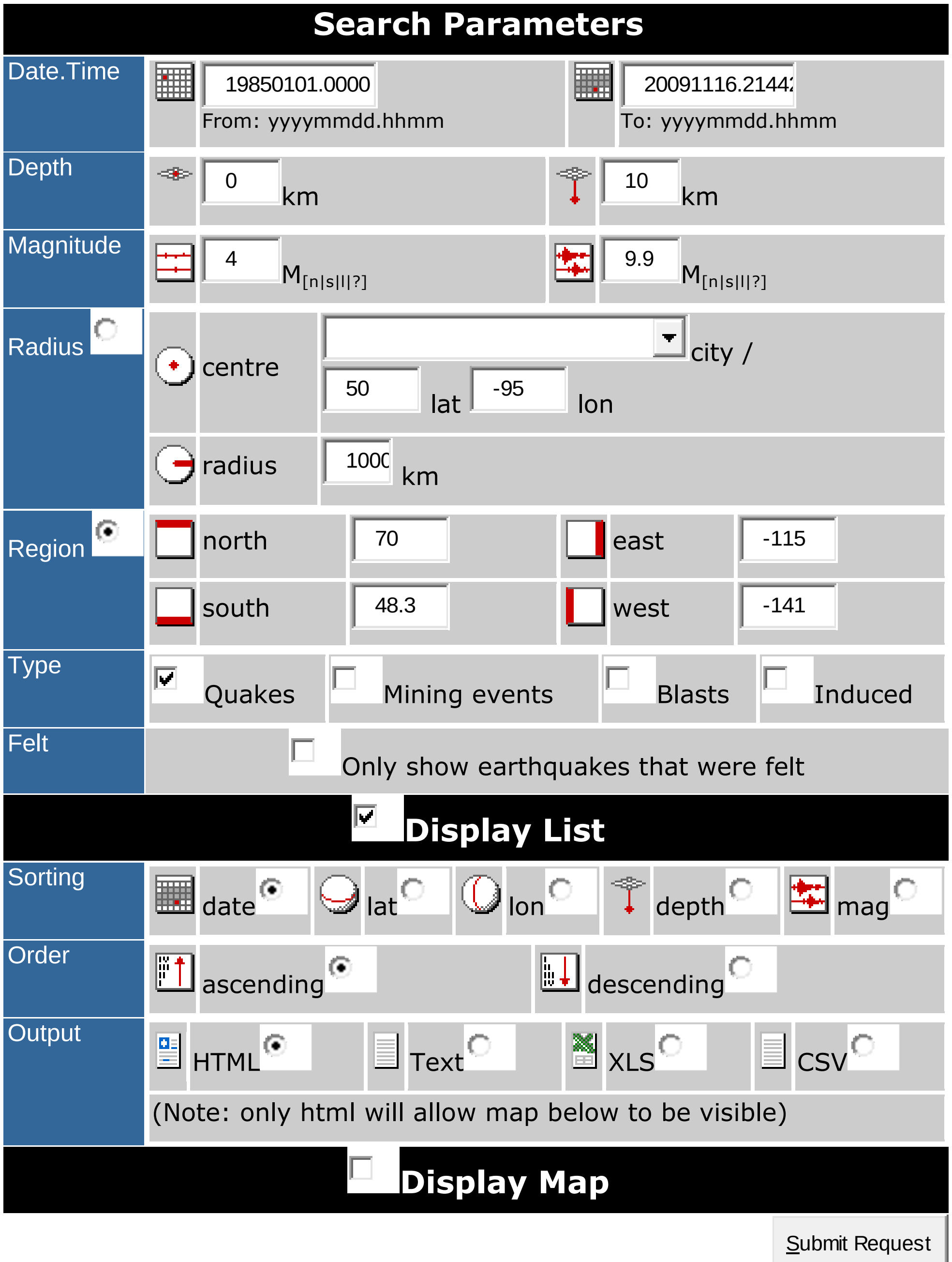
Appendix A: Calculated Temperature Gradients from the Canadian Geothermal Data Compilation

Unique Hole Number	Site name	Latitude	Longitude	Method	Temperature gradient ($^oC/km$)	Bottom hole depth (m)	Bottom hole temperature (^oC)	Log #
3001	Penticton	49.330	-119.627		38.08	609.9	33.320	Average of 4 logs
8001	Dease Lake	58.648	-130.001	Double and single thermistor probe	19.27	292.0	7.510	101921
9001	Hotailuh Batholith	58.160	-129.865	Double thermistor probe	27.88			
10001	Buckley Lake	57.893	-130.855	Double thermistor probe	31.41	424.9	15.240	
62001	North Cath	66.187	-138.693	Multi-thermistor cable	41.30	792.5	29.500	Average of 4 logs
63001	Reindeer	69.102	-134.615	Multi-thermistor cable	20.91	597.4	6.230	Average of 7 logs
70001	Providence	61.437	-117.375	Single thermistor probe	54.99	497.8	27.265	3 different logs
72001	Salmo	49.150	-117.190		32.33	821.7	33.627	Average of 2 logs
72002	Salmo	49.150	-117.183		31.54	624.0	30.580	Average of 2 logs
74001	Bluebell	49.753	-116.855		55.45	445.2	32.587	Average of 2 logs
78001-78006	Schaft Creek	57.350	-131.000	Single thermistor probe	18.43	278.6	7.473	100236
80001	McLeese Lake	52.518	-122.290	Single thermistor probe	17.53	287.7	9.984	100239
80002	McLeese Lake	52.520	-122.293	Single thermistor probe	15.55	231.6	8.344	100240
81001	Mt Polley	52.633	-122.555	Single thermistor probe	26.69	311.2	11.786	100241
81002-81006	Mt Polley	52.635	-122.558	Single thermistor probe	27.20	223.7	9.635	100242
89001	Beaver House Creek	68.372	-135.550	Single thermistor probe	36.43	1305.4	37.040	Average of 6 logs
100001	Hume River	65.867	-129.183	Single thermistor probe	57.36	281.9	14.762	Average of 2 logs
101001	Bralorne Mine	50.767	-122.800	Single thermistor probe	27.32	1501.7	46.820	100313
104001	Sullivan	49.700	-116.000	Single thermistor probe	26.40	911.4	27.102	Average of 15 logs
129001	Trout Lake	50.630	-117.600		23.80	522.7	13.567	1 log
160001	Gnat Lake	58.255	-129.817	Single thermistor probe	23.79	150.2	4.911	Average of 3 logs
163001	Myra Creek	49.576	-125.610	Single thermistor probe	15.53	779.7	17.548	Average of 2 logs
163002	Myra Creek	49.572	-125.590	Single thermistor probe	17.02	653.4	15.584	Average of 3 logs
180001	Sparwood	49.000	-115.000		31.80	214.8	10.426	Only used 1 log, others were highly variable
MC-18	Meager Creek	50.570	-123.508	Single thermistor probe	150.00	1200.0		
303002	Lillooet Valley	50.580	-123.280	Single thermistor probe	41.06	194.8	14.281	Average of 2 logs
304001	Squamish Valley	50.122	-123.393	Single thermistor probe	38.39	209.4	15.620	Average of 6 logs
305002	Granby River	49.418	-118.518	Single thermistor probe	47.13	444.1	32.520	Average of 14 logs
309001	Mount Cayley	50.085	-123.318	Single thermistor probe	96.00	453.2	52.540	
309002	Mount Cayley	50.073	-123.323	Single thermistor probe	53.95	444.1	31.787	Average of 9 logs
346001	Ucluet	49.020	-125.582	Single thermistor probe	14.79	99.7	10.053	1 log, Used data from below
346005	Adam River	50.358	-126.122	Single thermistor probe	3.92	98.4	7.449	1 log
346006	Salmon River	50.153	-125.703	Single thermistor probe	8.78	99.5	7.899	1 log, Used data below 60m
346007	Woss #1	50.225	-126.442	Single thermistor probe	8.47	90.4	7.422	1 log, Used data below 60m
346008	Klak Lake	50.140	-126.450	Single thermistor probe	5.61	99.6	7.769	1 log, Used data below 60m
346009	Woss #2	50.248	-126.708	Single thermistor probe	8.37	99.4	8.219	1 log, Used data below 60m
346010	Mahatta River	50.403	-127.768	Single thermistor probe	20.54	99.6	9.769	1 log, Used data below 60m
346011	Mahatta River	50.417	-127.792	Single thermistor probe	25.70	99.6	9.786	1 log, Used data below 60m
346012	Nahwitti River	50.762	-127.928	Single thermistor probe	21.89	99.6	9.155	1 log, Used data below 60m
346013	Nahwitti River	50.778	-127.930	Single thermistor probe	21.88	99.4	8.936	1 log, Used data below 60m
346014	Woss #3	50.258	-126.805	Single thermistor probe	4.75	76.6	8.290	1 log, Used data below 60m
346015	Woss #4	50.258	-126.803	Single thermistor probe	4.60	99.7	8.565	1 log, Used data below 60m
495001	Summerland	49.608	-119.688	Single thermistor probe	34.56	946.5	40.985	Average of 3 logs
706001	Kimberley	49.748	-116.045	Supplied by mining company	28.86	2608.0	80.400	1 log

Appendix B: Calculated Geothermometry values

Hot Spring Name	Location source	SiO_2	Na-K-Ca	Source	SiO_2 Geothermometer
Atlin	Fairbank (1992)	84	-13	Grasby et al. (2000)	Quartz (max)
Liard	Fairbank (1992)	134	33	Grasby et al. (2000)	Quartz (max)
Stikine	Fairbank (1992)	177	227	Fairbank (1992)	SiO2 (Fairbanks map)
Lakelse	Fairbank (1992)	154	74	Grasby et al. (2000)	Quartz (max)
Hot Springs Cove	Fairbank (1992)	89	55	Grasby et al. (2000)	Quartz (max)
Eucott Bay	Fairbank (1992)	113	87	Fairbank (1992)	SiO2 (Fairbanks map)
Talheo	Fairbank (1992)	141	98	Fairbank (1992)	SiO2 (Fairbanks map)
Canoe River (V2)	Ghomshei et al. (2010)	125	192	Ghomshei et al. (2010)	Quartz (max)
Hoodoo	Fairbank (1992)	135	195	SGP (2010)	Chalcedony
Canyon Lake	Fairbank (1992)	105	150	SGP (2010)	Chalcedony
Albert Canyon	see Grasby (2001)	96	34	Grasby et al. (2000)	Quartz (max)
Fair Harbour	Fairbank (1992)	104	89	Fairbank (1992)	SiO2 (Fairbanks map)
Pebble Ck.	Fairbank (1992)	122	139	NSBG (1974)	Quartz (max)
Meager Creek	Fairbank (1992)	170	188	Grasby et al. (2000)	Quartz (max)
Turbid Creek	Souther (1984)	131	171	Souther (1984)	Quartz (max)
Shovelnose	Souther (1984)	97	220	Souther (1984)	Quartz (max)
Halcyon	Fairbank (1992)	124	69	Grasby et al. (2000) an	Quartz (max)
Halfway	Fairbank (1992)	105	27	Grasby et al. (2000)	Quartz (max)
St. Leon	Fairbank (1992)	114	44	Grasby et al. (2000)	Quartz (max)
Nakusp	Fairbank (1992)	112	54	Grasby et al. (2000)	Quartz (max)
Radium 1-2	see Grasby (2001)	59	13	Allen et al. (2005)	Chalcedony cond (author)
Toby Creek	see Grasby (2001)	90	24	Allen et al. (2005)	Chalcedony cond (author)
Fairmont	see Grasby (2001)	59	15	Allen et al. (2005)	Chalcedony cond (author)
Red Rock	see Grasby (2001)	19	-2	Allen et al. (2005)	Quartz cond
Lucier Canyon 7-2	see Grasby (2001)	57	87	Allen et al. (2005)	Chalcedony cond (author)
Ram Creek 7-2	see Grasby (2001)	34	-3	Allen et al. (2005)	Chalcedony cond (author)
Buhl Creek/Skooku	see Grasby (2001)	42	66	Allen et al. (2005)	Chalcedony cond (author)
Sloquet Creek	Fairbank (1992)	115	36	Grasby et al. (2000) an	Quartz (max)
Clear Ck.	Fairbank (1992)	123	38	Fairbank (1992)	SiO2 (Fairbanks map)
Harrison	Fairbank (1992)	141	90	Grasby et al. (2000) an	SiO2 (Fairbanks map)
Dewar Creek	Fairbank (1992)	157	149	Grasby et al. (2000)	Quartz (max)
Ainsworth	Fairbank (1992)	153	87	Grasby et al. (2000) an	Quartz (max)
Crawford Bay	Fairbank (1992)	66	29	Fairbank (1992)	SiO2 (Fairbanks map)
Wild Horse	see Grasby (2001)	49	7	Allen et al. (2005)	Chalcedony cond (author)
Fording Mountain	see Grasby (2001)	23	67	Allen et al. (2005)	Chalcedony cond (author)
15b	Michel et al. (2002)	0	-15	Michel et al. (2002)	Quartz (max)
5 (1984)	Michel et al. (2002)	11	71	Michel et al. (2002)	Quartz (max)
6b (1983)	Michel et al. (2002)	81	23	Michel et al. (2002)	Quartz (max)
Basin	see Grasby (2001)	81	7	Grasby et al. (2000)	Quartz (max)
Cave	see Grasby (2001)	76	5	Grasby et al. (2000)	Quartz (max)
DDH-1: 549m	Michel et al. (2002)	26	82	Michel et al. (2002)	Quartz (max)
DDH-3: 385m	Michel et al. (2002)	51	57	Michel et al. (2002)	Quartz (max)
DDH-4: 183m	Michel et al. (2002)	33	-5	Michel et al. (2002)	Quartz (max)
Middle	see Grasby (2001)	80	6	Grasby et al. (2000)	Quartz (max)
Mist Mountain	see Grasby (2001)	72	-13	Grasby et al. (2000)	Quartz (max)
Upper	see Grasby (2001)	89	8	Grasby et al. (2000)	Quartz (max)
Wolfenden	see Grasby (2001)	28	33	Allen et al. (2005)	Chalcedony cond (author)

Appendix C: Earthquake Search Parameters



Search Parameters

Date.Time	19850101.0000 From: yyyymmdd.hhmm	20091116.2144; To: yyyymmdd.hhmm
Depth	0 km	10 km
Magnitude	4 M[n|s|l|?]	9.9 M[n|s|l|?]
Radius	centre: city / 50 lat -95 lon	radius 1000 km
Region	north 70; south 48.3	east -115; west -141
Type	Quakes; Mining events; Blasts; Induced	
Felt	Only show earthquakes that were felt	

Display List

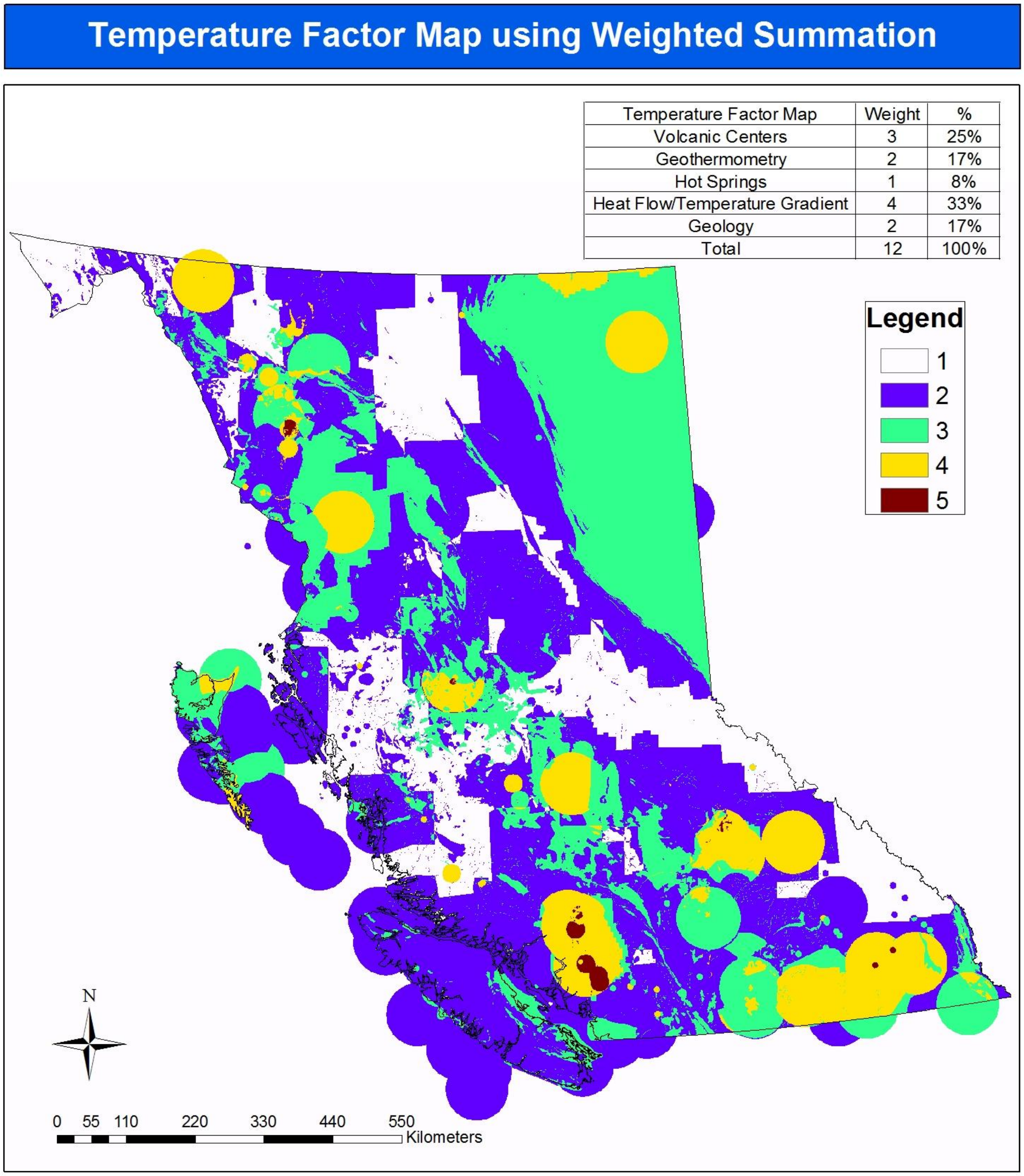
Sorting	date; lat; lon; depth; mag
Order	ascending; descending
Output	HTML; Text; XLS; CSV (Note: only html will allow map below to be visible)

Display Map

Submit Request

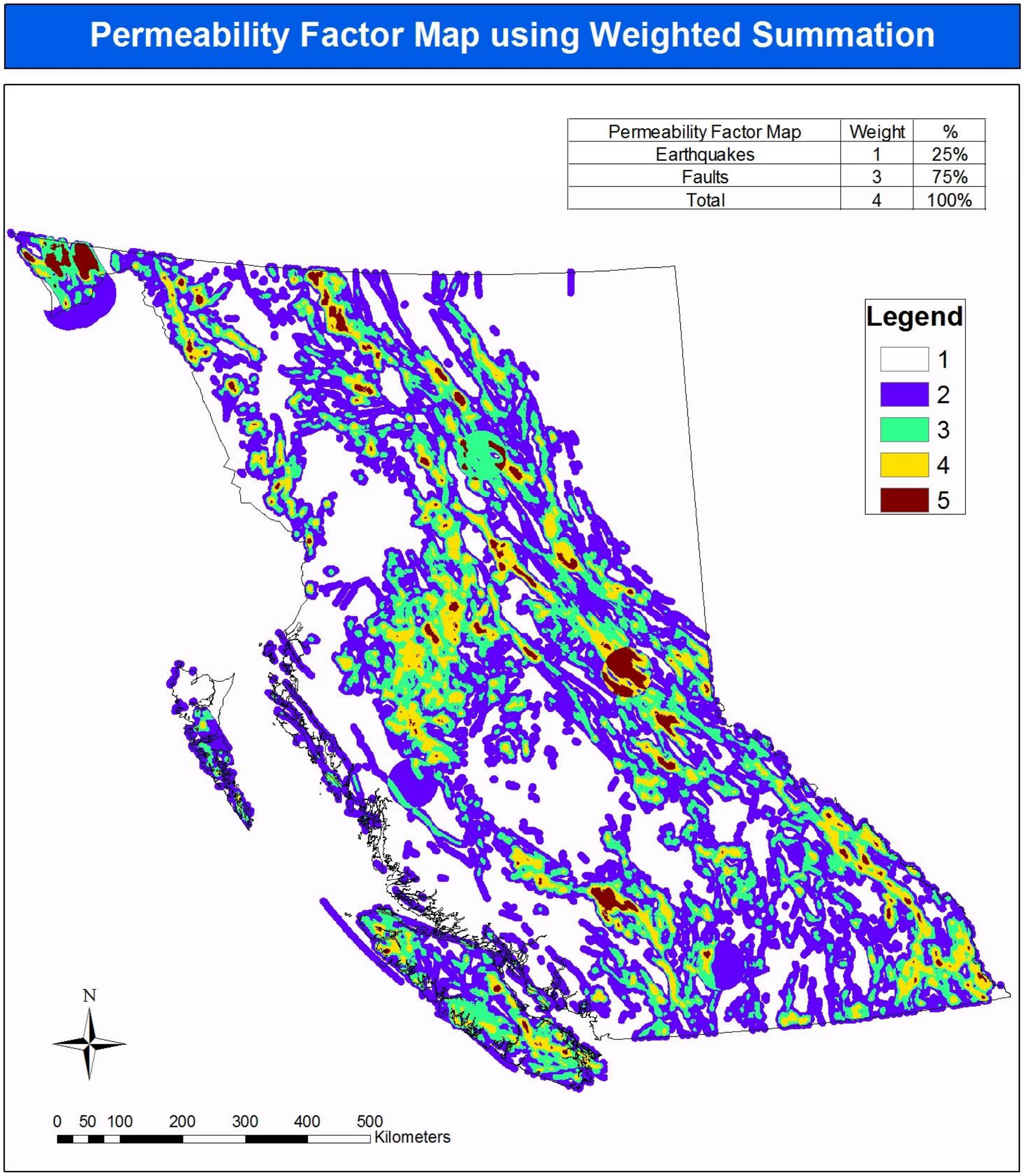
Note: Date.Time 19850101.0000 is the earliest date for which earthquake events were recorded in the online database. The search generated 941 records.

Appendix D: Weighted Summation Temperature Factor Map

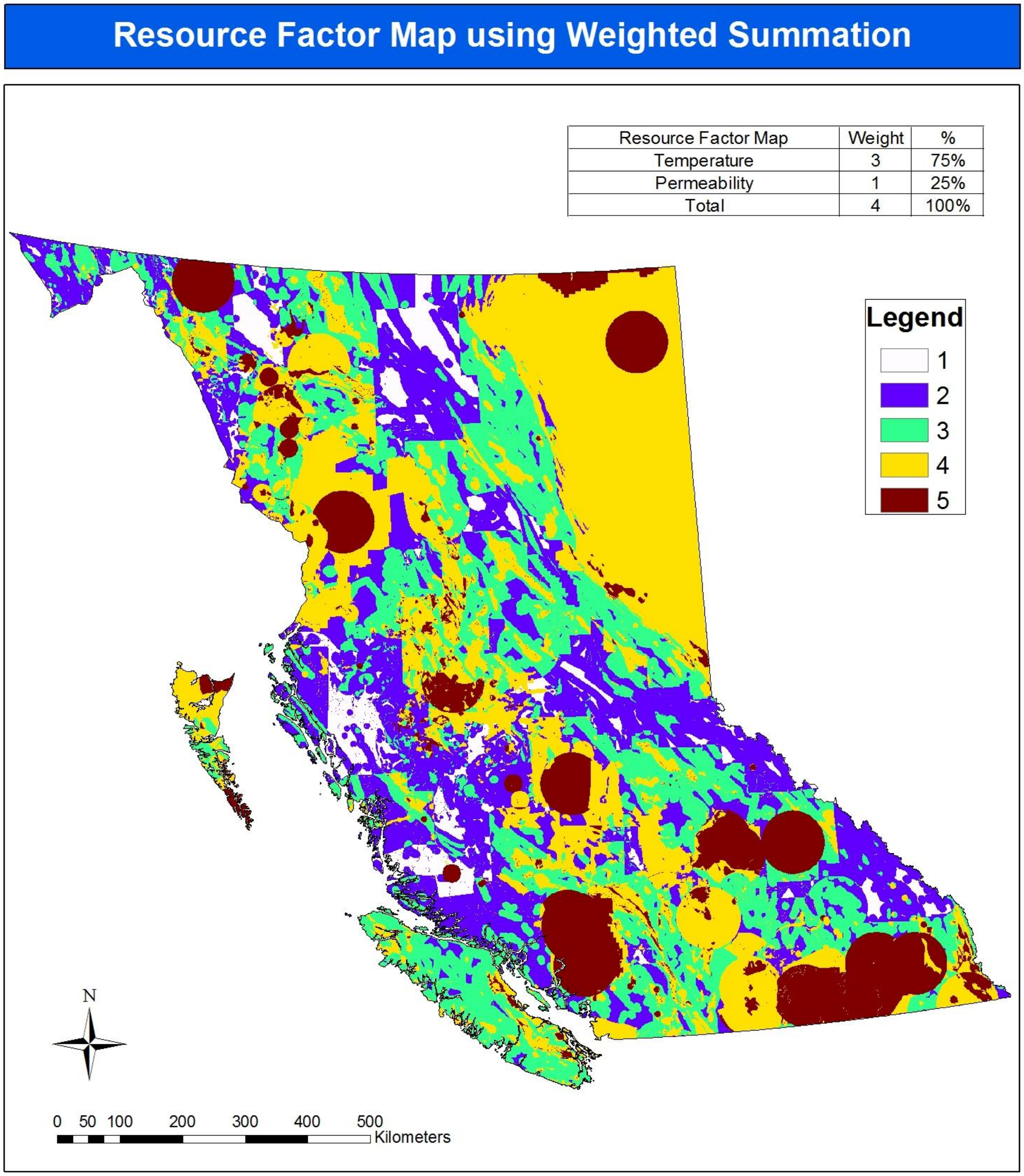


Temperature Factor Map	Weight	%
Volcanic Centers	3	25%
Geothermometry	2	17%
Hot Springs	1	8%
Heat Flow/Temperature Gradient	4	33%
Geology	2	17%
Total	12	100%

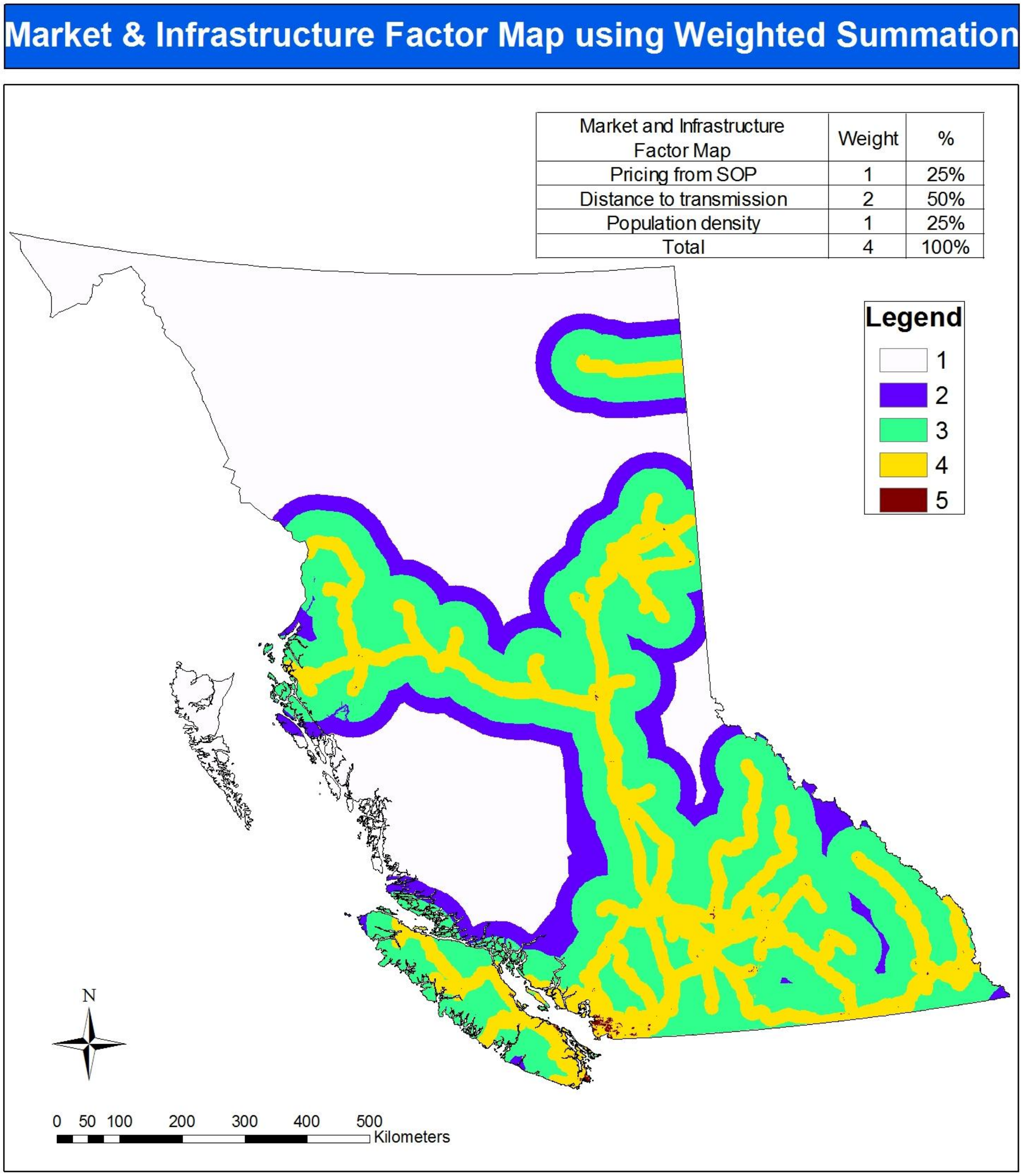
Appendix E: Weighted Summation Permeability Factor Map



Appendix F: Weighted Summation Resource Factor Map



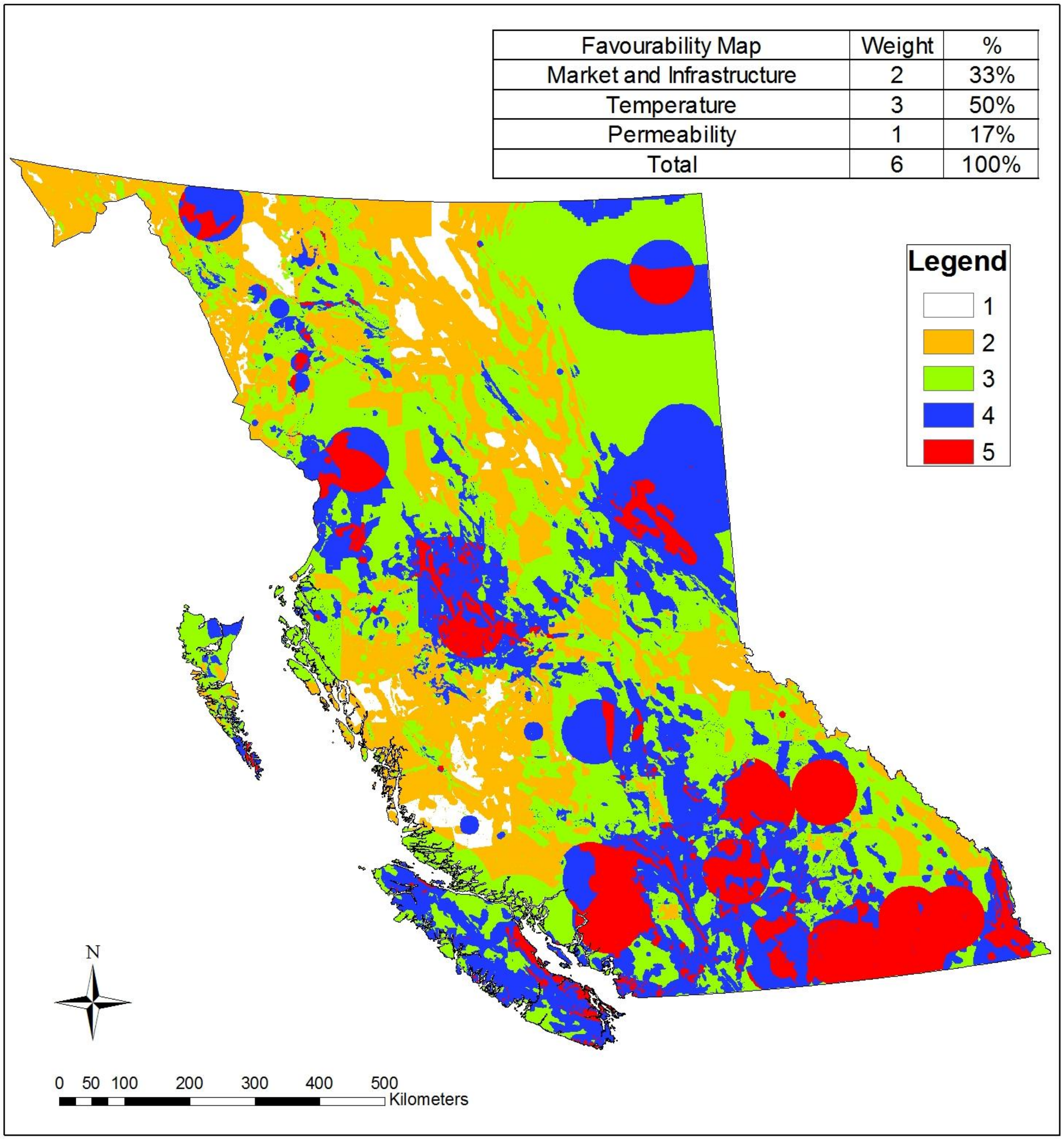
Appendix G: Weighted Summation Market & Infrastructure Factor Map



Appendix H: Weighted Summation Geothermal Favourability Map

Geothermal Favourability Map using Weighted Summation

Favourability Map	Weight	%
Market and Infrastructure	2	33%
Temperature	3	50%
Permeability	1	17%
Total	6	100%



Appendix I: Eigenvalues and Eigenvectors from the AHP output

Temperature Factor Map:

[Criteria & LayerSource (clsfd.)]					
Volcanic Centers EL	Volcanic Centers EL				
Geothermometry EL	Geothermometry EL				
Hot Springs EL	Hot Springs EL				
Temperature EL	Temperature EL				
Geology EL	Geology EL				
[Preference Matrix]					
	Volcanic Centers EL	Geothermometry EL	Hot Springs EL	Temperature EL	Geology EL
Volcanic Centers EL	1	2	3	0.5	3
Geothermometry EL	0.5	1	2	1	3
Hot Springs EL	0.3333	0.5	1	0.3333	2
Temperature EL	2	1	3	1	3
Geology EL	0.3333	0.3333	0.5	0.3333	1
[*****AHP results*****]					
[Eigenvalues]					
5.1905					
-0.0757					
-0.0757					
-0.0195					
-0.0195					
[Eigenvector of largest Eigenvalue]					
0.5604					
0.4406					
0.2238					
0.6457					
0.1577					
[criteria weights]					
27.63%	(Volcanic Centers EL)				
21.73%	(Geothermometry EL)				
11.03%	(Hot Springs EL)				
31.84%	(Temperature EL)				
7.77%	(Geology EL)				
[consistency ratio CR]					
0.0425					
(Revision of preference values is recommended if CR > 0.1)					

Permeability Factor Map:

[Criteria & LayerSource (clsfd.)]		
Fault density EL	Reclass_line1	
Earthquakes EL	Earthquakes EL	
[Preference Matrix]		
	Fault density EL	Earthquakes EL
Fault density EL	1	8
Earthquakes EL	0.125	1
[*****AHP results*****]		
[Eigenvalues]		
2		
0		
[Eigenvector of largest Eigenvalue]		
0.9923		
0.124		
[criteria weights]		
0.8889	(Fault density EL)	
0.1111	(Earthquakes EL)	
[consistency ratio CR]		
0		
(Revision of preference values is recommended if CR > 0.1)		

Resource Factor Map:

[Criteria & LayerSource (clsfd.)]		
Reclass_Temp1	Reclass_Temp1	
permfm_re	permfm_re	
[Preference Matrix]		
	Reclass_Temp1	permfm_re
Reclass_Temp1	1	4
permfm_re	0.25	1
[*****AHP results*****]		
[Eigenvalues]		
2		
0		
[Eigenvector of largest Eigenvalue]		
0.9701		
0.2425		
[criteria weights]		
80.00%	(Reclass_Temp1)	
20.00%	(permfm_re)	
[consistency ratio CR]		
0		
(Revision of preference values is recommended if CR > 0.1)		

Market and Infrastructure Factor Map

[Criteria & LayerSource (clsfd.)]			
Population density EL	Reclass of reclass5_pop		
SOP Price EL	SOP EL		
Transmission EL	Transmission EL		
[Preference Matrix]			
	Population density EL	SOP Price EL	Transmission EL
Population density EL	1	0.3333	0.1111
SOP Price EL	3	1	0.1667
Transmission EL	9	6	1
[*****AHP results*****]			
[Eigenvalues]			
3.0536			
-0.0268			
-0.0268			
[Eigenvector of largest Eigenvalue]			
0.086			
0.2048			
0.975			
[criteria weights]			
6.79%	(Population density EL)		
16.18%	(SOP Price EL)		
77.03%	(Transmission EL)		
[consistency ratio CR]			
0.0515			
(Revision of preference values is recommended if CR > 0.1)			

Favourability Map:

[Criteria & LayerSource (clsfd.)]		
Reclass_Reso1	Reclass_Reso1	
mifm_re	mifm_re	
[Preference Matrix]		
	Reclass_Reso1	mifm_re
Reclass_Reso1	1	5
mifm_re	0.2	1
[*****AHP results*****]		
[Eigenvalues]		
2		
0		
[Eigenvector of largest Eigenvalue]		
0.9806		
0.1961		
[criteria weights]		
83.33%	(Reclass_Reso1)	
16.67%	(mifm_re)	
[consistency ratio CR]		
0		
(Revision of preference values is recommended if CR > 0.1)		