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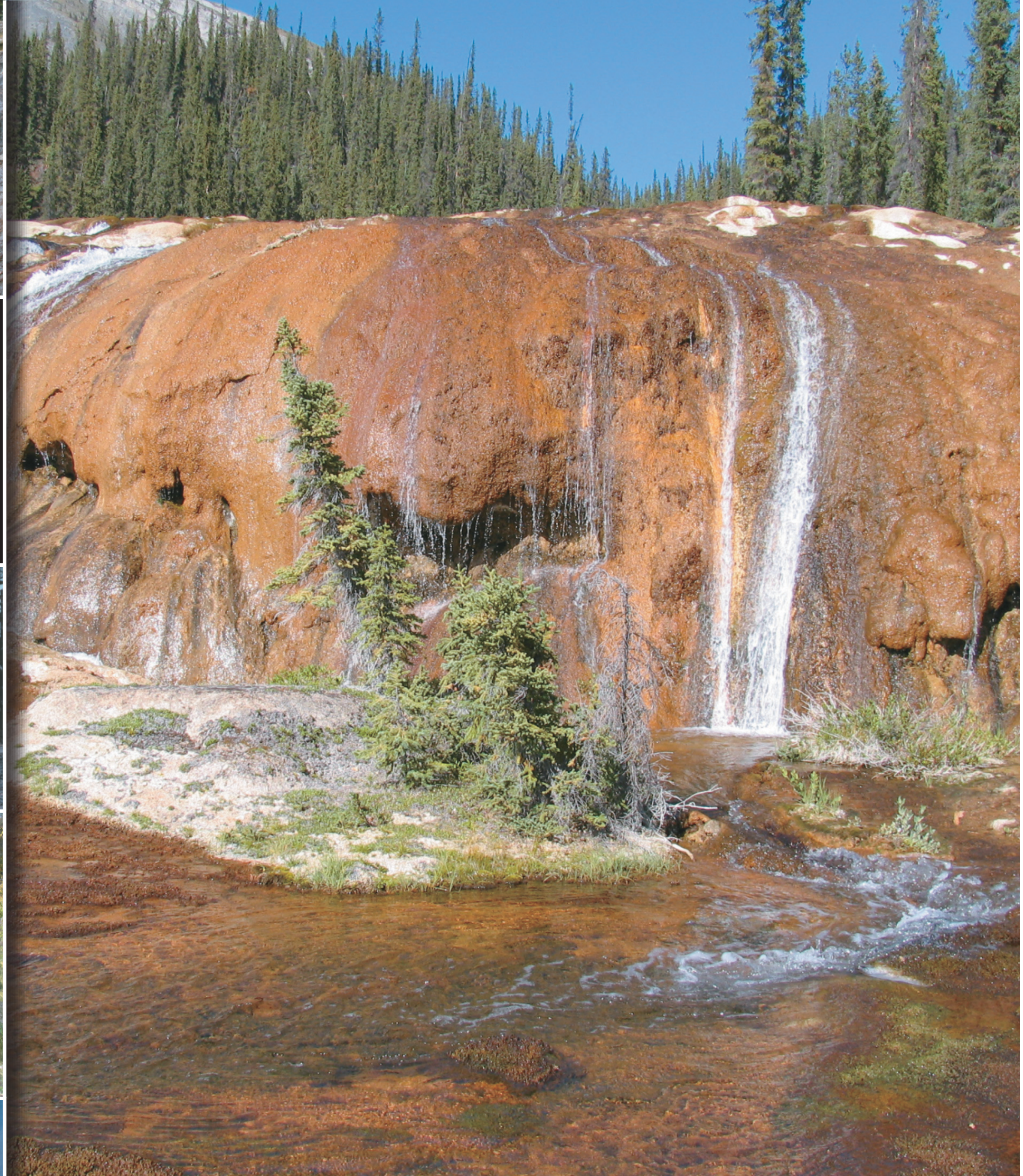

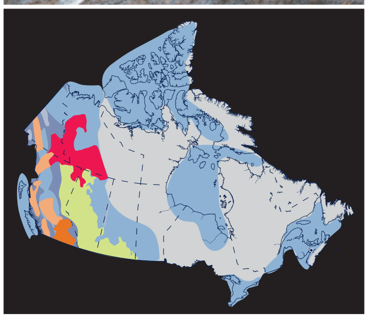

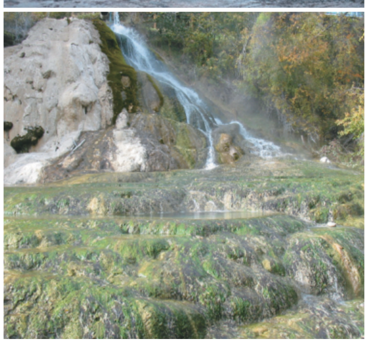

Geothermal Energy Resource Potential of Canada

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CONTENTS

EXECUTIVE SUMMARY

KEY BULLETS

- Canada has enormous geothermal energy resources that could supply the country with a renewable and clean source of power; currently Canada has no geothermal electrical production.
- The high capacity factor of geothermal power makes geothermal energy particularly attractive as a renewable base load energy supply.
- Geothermal energy potential is broadly distributed across Canada, however, there are only sufficient data to characterize geothermal potential for 40% of Canada's landmass.
- Canada's in-place geothermal power exceeds one million times Canada's current electrical consumption, although only a fraction of this can likely be produced.
- Remote northern communities could be the first to benefit from geothermal development in Canada.
- Canada has significant potential for EGS development, as few as 100 projects could meet a significant fraction of Canada's base load energy needs.
- Research on decreasing installation costs could make feasible further exploitation of abundant low-temperature geothermal resources.
- Environmental impacts of geothermal development are relatively minor compared to other energy developments, however there are still key issues to be addressed
- Geothermal installations have the potential to displace other more costly and environmentally damaging technologies.
- Geoscience research and mapping is required to reduce exploration risk as well as to support regulatory development in order to attract industry investment.

INTRODUCTION

Canada has enormous geothermal energy resources that could supply a renewable and clean source of power. There are many constraints, however, in utilizing this energy resource, including geological, technical, and regulatory issues. The intent of this report is to examine the geothermal potential in Canada, and the geological controls on the distribution of high grade resources as well as controls on the economic development and production of geothermal energy. This assessment is based on a new compilation and digitization of data produced through over 48 years of geothermal research in Canada. Recommendations on current and future research needs to reduce barriers to resource production are made at the end of the report.

Currently Canada has no geothermal electrical production; however, direct use and heat exchange systems are used widely. Several projects are currently being examined by industry and government to develop electrical potential in Canada. A key economic constraint for these projects is the high risk of exploration due to costs of deep drilling. **The cost of delivered geothermal power is projected to decline and be competitive with coal fired production within the next 15 years**, given current levels of technology.

Canada's in-place geothermal power exceeds one million times Canada's current electrical consumption (Fig. 1). However, only a fraction of this total potential could be developed. Much of the resource lies beyond current drilling technology, outside of areas served by high-capacity transmission lines, and at some distance from load centres. Nonetheless, the available high grade geothermal resource is considerable. High temperature hydrothermal systems can be brought on line with proven technology. Many of the tools required to bring geothermal energy to full realization, however, are not commercially proven to date and require further research and technology development. We can expect a strong learning curve and price response as geothermal energy is developed while other energy sources such as coal and nuclear will begin to see fleet and capacity retirements.

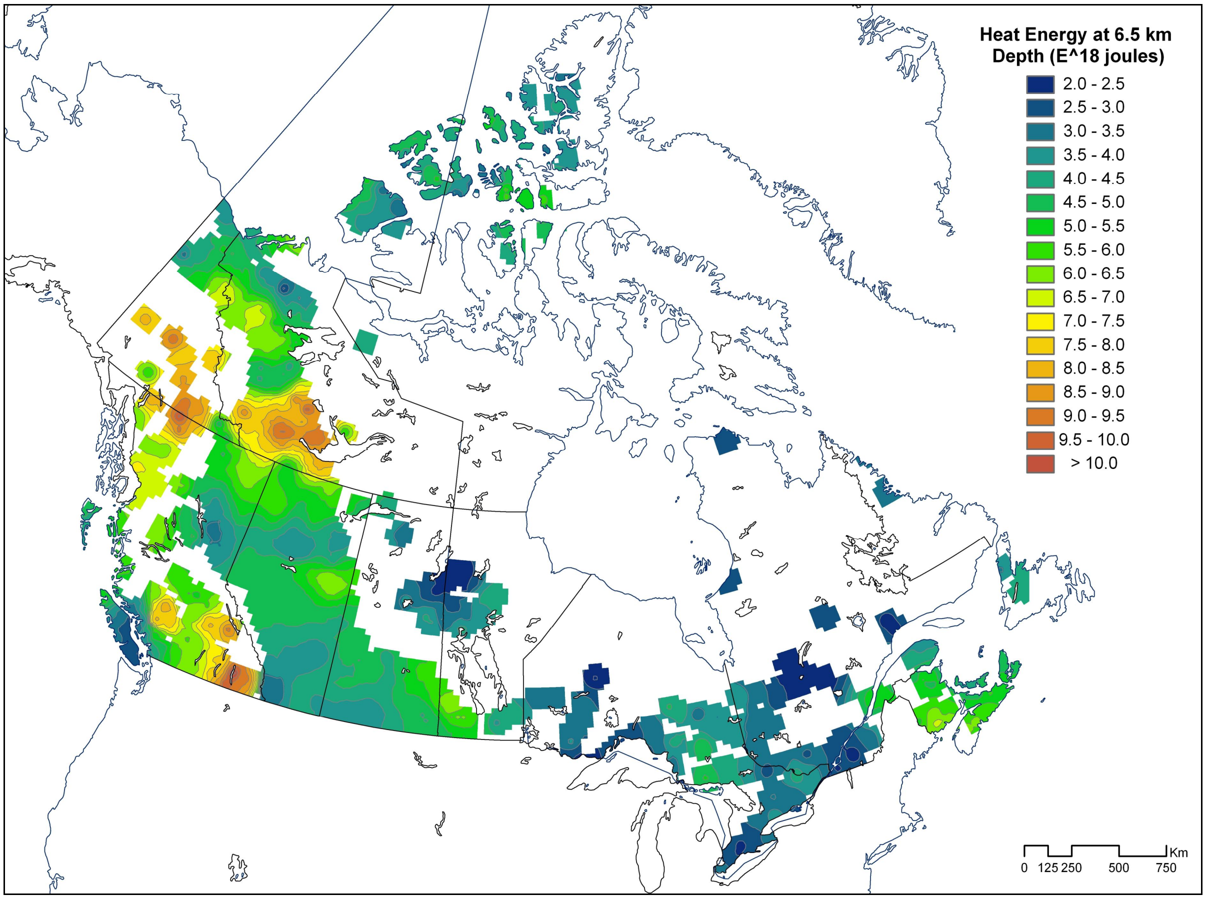


Figure 1 Map showing example of in-place geothermal energy for 6-7 km depth across Canada. Similar in-place energy is found at shallower and deeper levels.

GEOTHERMAL ENERGY

Geothermal energy is derived from heat produced in the subsurface. Heat is generated from natural radiogenic decay of elements in the upper crust as well as primordial heat generated from the formation of the planet. While there is a natural flow of heat from depth to the surface anywhere on Earth, local geological processes can lead to anomalous high-temperature geothermal resources that are within economic drilling depths. Geothermal resources are broadly characterised by their temperature range. High and medium temperature resources are used globally for stable base-load electrical generation. **The high capacity factor of geothermal power makes it particularly attractive as a renewable resource**. The most efficient and economic means to generate geothermal power include binary-cycle plants, flash steam plants and dry steam plants. High temperature resources (> 150 °C) are typically targeted for this application. Although not as efficient, electricity generation is still feasible and economic at temperatures as low as 80 °C.

Apart from having a thermal anomaly, conventional geothermal resources must be located at a depth accessible by drilling, and must have a sufficiently large body of permeable rock from which geothermal waters can be produced in order to carry heat to the surface. Enhanced Geothermal Systems (EGS), a new type of geothermal power technology, does not require naturally occurring permeable rock nor in situ thermal waters. Instead this evolving technology is used to "enhance" high temperature rocks at depth. **Successful development of EGS technology promises to greatly broaden the regions with geothermal electrical generation potential.**

Medium to low temperature resources are primarily used for direct space heating of residences and commercial buildings, or other similar applications (e.g. greenhouses). Where shallow ground temperatures remain relatively constant and lower than normal room temperature (20 °C) throughout the year, heat pumps may be employed to facilitate energy recovery.

DISTRIBUTION OF GEOTHERMAL RESOURCE

Geothermal energy potential is broadly distributed across Canada (Figure 2). Knowledge of the geological framework of Canada can significantly reduce exploration risk by defining regions with the best geological conditions to host a geothermal resource.

Volcanic belts are common in the Canadian Cordillera, and those formed in the last 5 million years are likely still hot enough to host extensive high temperature geothermal resources. Many of Canada's volcanoes are poorly characterised, and there is a lack of knowledge of their ages, making assessment of higher potential volcanic regions difficult. Many younger intrusive rocks (magma that solidifies underground) also have significant heat generation potential from abundant radioactive isotopes. While locations of these features are known, there is very limited data on the heat generation potential and thermal gradients.

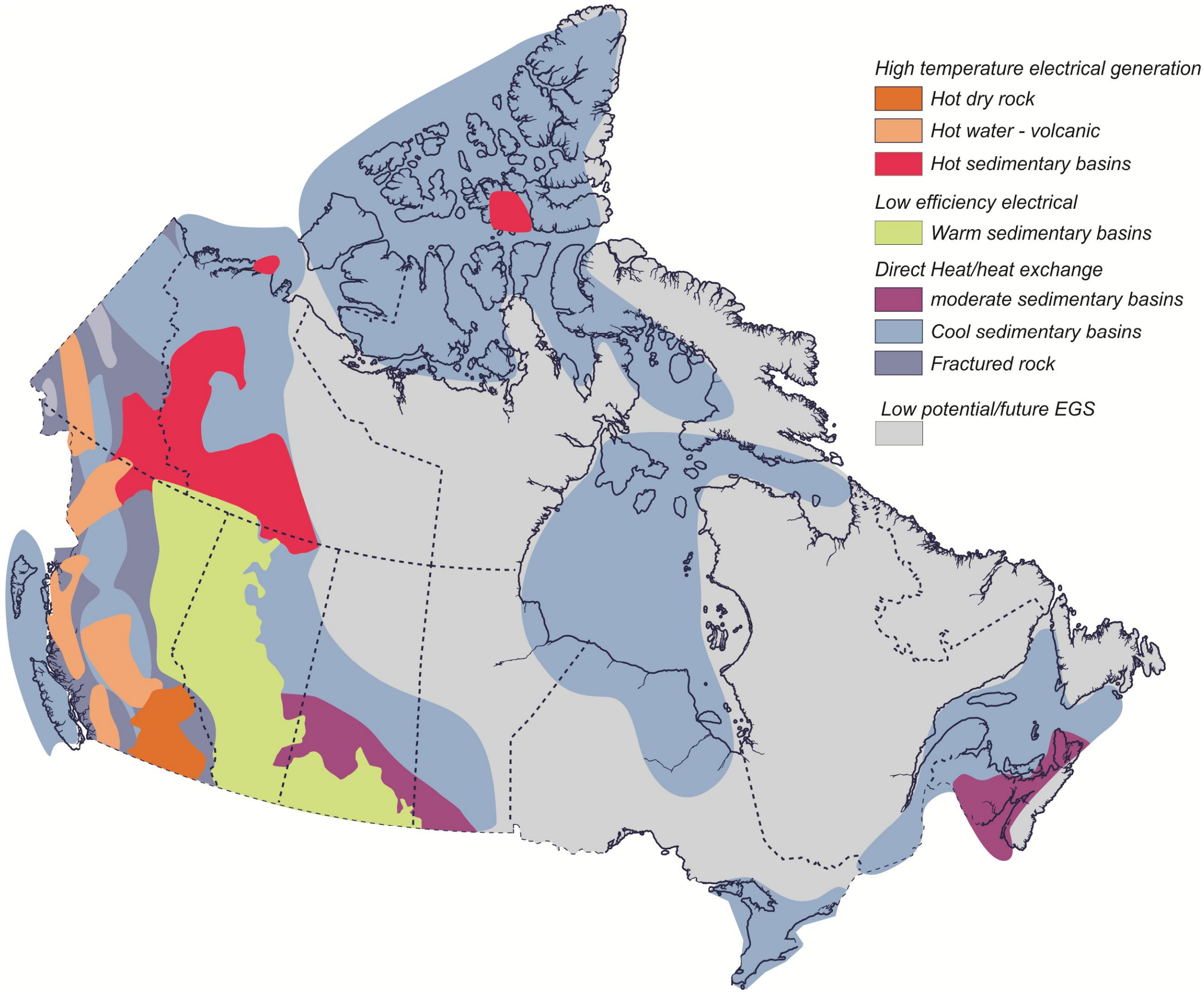


Figure 2. Map showing distribution of geothermal potential in Canada based on end use.

Outside major volcanic belts the Canadian Cordillera shows large variability in heat flow, with distinct regions that show great potential for geothermal resources. Abundant thermal springs (over 140 in Canada) are seen as a key exploration tool for defining areas with geothermal potential. Thermal springs can also provide means for direct use of geothermal energy by capturing the flow for various uses - from spas to direct heating. Currently Canada has 12 developed thermal spring pools. However, unique and rare ecosystems are commonly associated with thermal spring outlets and their protection needs to be considered in any development plans.

Canada is covered by extensive sedimentary basins that contain a great deal of warm to hot fluid in porous rocks. Geothermal resources of sedimentary basins in Canada are typically moderate to low temperature. Locally, however, temperatures that exceed 150 °C are known at depths as shallow as 3 km. **These high temperatures allow potential for electrical generation in regions of northeastern British Columbia, northern Alberta and southern Northwest Territories.** Petroleum wells provide significant data for some areas (temperature measurements that likely number in the millions): however, the data are of variably quality. A significant challenge remains to compile digital records and verify accuracy of these data. While basins with an extensive exploration history have detailed knowledge of temperatures, geothermal gradients and sediment thickness, other basins have very limited information.

The Canadian Shield represents a large geographic region, extending from the Arctic Archipelago, south to eastern and central Canada. The shield is characterized by igneous and metamorphic rock composed of some of the oldest crustal rocks on Earth (3.96 billion years old). Given the great age of these rocks radiogenic elements have all undergone significant radioactive decay and current heat generation in the Canadian Shield is very low. As well, the thermal conductivity of granitic and gneissic rocks which dominate the Canadian Shield is significantly higher than sedimentary rocks, meaning that any heat generated is readily conducted to the surface, lowering geothermal gradients. Although for large portions of this area no data exist, the Shield region apppears to have the lowest geothermal energy generation potential in Canada. Conversely, the potential for heat exchange using heat pumps is attractive due to the high thermal conductivity of the host rock.

PREVIOUS GEOTHERMAL RESEARCH

Geothermal research has been conducted for many years in Canada. A geothermics program was started in 1962. In 1976 the Department of Energy Mines and Resources (Natural Resources Canada predecessor department) initiated The National Geothermal Energy Program that ran until March 31st 1986, with a total budget of $6 million (in 1980's dollars). This program was responsible for the collection of much of the geothermal data that currently exists for Canada, and provided the initial definition of regions of Canada with the highest resource potential. The program included cooperative demonstration projects as well as technical assistance to various government agencies interested in geothermal developments. The program was terminated in response to drop in petroleum prices in 1986, which made most renewable energy resources uncompetitive. It is worthy to note however that costs of carbon emissions were not accounted for at that time.

The National Geothermal Energy Program defined significant geothermal energy potential in Canada. A successful demonstration project at Meager Mountain in British Columbia discovered resources up to 290 °C, and culminated in the first electrical generation by geothermal power in Canada by a 20 kilowatt demonstration plant. While a success, this project was not connected to the grid and has since been left in a pre-development stage. A second successful demonstration project involved drilling a well for direct heating application on the University of Regina campus. While testing showed that the well met all criteria to provide required heat energy, the building it was meant to heat was not constructed (there are recent discussions to revive this project). A third project using heat in flooded abandoned mines focused on Springhill, Nova Scotia. This project resulted in long term reduction of energy costs and CO_2 emissions for industry using the flooded mines as a geothermal reservoir.

CANADIAN GEOTHERMAL POTENTIAL

Extensive effort to compile and convert historic data to digital format was undertaken to allow a current assessment of geothermal potential in Canada. Along with basic temperature measurements, knowledge of heat flow, geothermal gradients (the rate at which temperature increases with depth), thermal conductivity of rocks (the rate at which heat is conducted), and thermal diffusivity (required for modeling time-related heat transfer and the long term sustainability of the geothermal resources) are required to define resource potential. In addition, framework geology and basic knowledge of porosity, permeability and water geochemistry are required. Some parameters are well characterized (for parts of Canada), while comprehensive databases are lacking for others. These data only exist in certain regions of the country, and there remain large regions of Canada with sparse or no data. We estimate that **there are sufficient data to characterize, to some degree, geothermal potential of only 40% of Canada's landmass**. From this some general descriptions can be made.

Heat flow in the Canadian Cordillera is similar to the western USA Basin and Range (the region producing the most geothermal power in the world). The highest heat flow values measured in Canada occur in the Garibaldi volcanic belt (>200 mW/m^2). Other regions of very high heat flow occur in parts of western Canada, particularly in northwestern Alberta, northeastern British Columbia, southwestern Northwest Territories, and the southern Yukon. High heat flow values are also found in the Mackenzie Corridor, in the foreland basins of the Northwest Territories, and in the eastern part of the Tuktoyaktuk Peninsula in the Beaufort-Mackenzie area. Elevated heat flow is also observed in the Appalachian region in Eastern Canada. In general, high heat flow regions in Canada's High Arctic are in areas with little or no population. However, there are some isolated communities (e.g. Resolute Bay) near high heat flow areas that are dependant on diesel for all their energy needs, which that may benefit from a local geothermal resource base. **Remote northern communities could be the first to benefit from geothermal development in Canada.**

Mapping of temperatures at depths of 3.5, 6.5, and 10 km show that temperatures suitable for geothermal electrical generation (>150 ^{o}C) can be reached over large areas of Canada. Overall, temperatures are highest in western Canada, reaching 150 ^{o}C at depths of 3.5 km in limited areas of the Canadian Cordillera and in the southern part of the Mackenzie Corridor. At depths of 6.5 km, large areas of the Canadian Cordillera and parts of western Canada show temperatures of 150 to 200 °C. These represent the best target areas under the most likely limit of drilling depths, as based on drilling costs and technical abilities in the foreseeable future. However, drilling to depths of 10 km is potentially feasible in the future and these depths have already been achieved (e.g. the deep drilling project on the Kola Peninsula). At 10 km depth, EGS temperatures in the 150 to 200 °C range can be expected across most of Canada, except in some areas of the Canadian Shield. At this depth, temperatures in the 200 to 300 °C range are estimated for large regions of western Canada.

Most of Canada, in the non-permafrost areas, has shallow ground temperatures at 50 m depth as much as 7 °C higher than the mean surface temperature measured at meteorological stations. This implies that a large amount of thermal energy is stored in the shallow geological environment, which can be exploited for heat-exchange systems. **Development of heat-exchange systems has been proceeding rapidly, but the shallow heat-exchange resource is still largely untapped**.

Canada's long mining history has left abundant mines across the country, which are typically located close to communities built for mine workers. Abandoned mine sites contain large volumes of groundwater and surface water, that can be used for space cooling and heating with ground source heat pump systems. Mine workings act as a heat exchanger, greatly reducing the capital investment required as compared to conventional ground source heat pump systems. The first heat pump system reported to operate from an abandoned mine was installed in 1989 in Springhill, Nova Scotia, making Canada a world leader in this application.

The inventory of geothermal resources associated with mine sites is currently incomplete because data are missing for several provinces. However preliminary estimates can be made for regions of Canada with sufficient data. The inventory carried out in British Columbia, Alberta, Saskatchewan, Québec and Nova Scotia revealed 2262 abandoned mines. Lists of abandoned mines for some provinces were not available. Geothermal resources hosted by mines can be exploited within a few kilometers of mine sites only. Potential targets for geothermal operations were identified from coast to coast, including near Nanaimo, Abbotsford, Kamloops, Penticton, Parkland County, Edmonton, Medicine Hat, Rouyn-Noranda, Val D'Or, Sherbrooke, Thetford Mines, Halifax, New Glasgow, Sydney and Glace Bay.

ENHANCED GEOTHERMAL SYSTEMS

Although many regions of Canada have high temperature resources, not all are suitable for geothermal development due to a lack of water, or low permeability or porosity of the host rocks. For these areas Enhanced (or Engineered) Geothermal Systems (EGS) can artificially create reservoirs to extract economical amounts of heat. This concept is currently the subject of several research studies internationally and once brought to successful production, will greatly broaden the regions where geothermal energy production is feasible. EGS systems have significant advantages over conventional hydrothermal systems that must be located near easily-accessible hot water resources. EGS systems do not require in situ water, nor an initial high permeability of the reservoir, making application of this technology largely only restricted by adequate heat supply at reasonable drilling depths. Practical use of EGS resources has been demonstrated in several projects, including Soultz-sous-Forêts, Alsace, Hot Dry Rock in Europe (BGR, 2008), and the Cooper Basin in Australia. Additional research on EGS systems is underway in other countries.

Canada has significant potential for EGS development. The best EGS prospects are in western Canada due to high overall heat flow. The most promising targets for EGS are in the Canadian Cordillera, particularly in southern British Columbia and in the southern part of the Yukon. Additionally, the

Mackenzie Basin, northeastern British Columbia, northwestern and central Alberta and parts of Saskatchewan are areas that have high potential for EGS development. **While the technology to develop EGS systems is still developing, calculations suggest as few as 100 projects could meet Canada's energy needs.**

Subsurface rocks are under confining pressures related to the regional stress field. The orientation of the stress field influences the directions in which fractures open and propagate in the subsurface, controlling directions of preferential fluid movement through rock and what pressures are required to propagate fractures. Identifying the orientations of possible open fractures can provide valuable insights for developing geothermal prospects. This knowledge can aid spacing and location of injection and production wells, maximizing potential for heat recovery while minimizing seismic risk. Abundant data from petroleum exploration allows assessment of the regional stress regime in western Canada. Much of the region is under a coherent stress regime, which is consistent with the broader North American stress patterns. This knowledge allows geothermal developments to maximize efficiency of design of subsurface heat exchangers. However local scale stress studies would still be required to account for local deviations from regional trends. However, **few stress orientations and magnitudes have been measured at the depths needed for geothermally-powered electrical generation**. Additionally, data on stress orientations and magnitudes are generally limited to the Western Canada Sedimentary Basin, so many other regions of high geothermal potential have very limited stress field data.

ENVIRONMENTAL IMPACTS

As with any industrial development, pre-planning to avoid or minimize environmental impacts for geothermal development is required. **Impacts of geothermal development are relatively minor compared to many other energy developments, however there are still key issues to be addressed**. Low-temperature geothermal systems have the potential to negatively affect shallow groundwater systems through changes in temperature fields that may cause mineral precipitation or affect microbial growth. In addition, thermal plumes may develop where shallow systems are present in areas of significant groundwater flow. Changes in groundwater temperatures may eventually impact surface streams where groundwater discharge occurs, and which may in turn impact biological systems with temperature sensitivity. For closed loop geothermal systems, organic fluids are circulated through the shallow groundwater, where potential leakage could cause contamination. Shallow geothermal systems need to be managed in such a way as to protect potable groundwater resources and ecosystems.

Geothermal power developments, produced from medium to high-temperature resources, will have similar impacts as direct-use applications but at a much larger scale. The habitat surrounding a geothermal development can vary site-by-site, providing unique biological, chemical and geological conditions that few species are able to adapt to. Geothermal habitats are also found most commonly in tectonically active zones, and at times in incompetent rock, which can contribute to land erosion, subsidence and seismicity when subsurface fluids are removed or when land is disturbed. With the development of EGS technology, where wells are hydraulically fractured, these risks have the potential to increase. Although land use requirements for geothermal development are substantially lower in comparison with other energy developments, mitigation strategies such as reinjection of waste water, continuous monitoring of areas naturally prone to seismicity or land slides, as well as an in-depth knowledge of site characteristics may be used to avoid possible threats to key geothermal habitats.

Various effluents in the form of incondensable gases and trace elements can be found naturally in subsurface aquifers and geothermal waters. Carbon dioxide (CO_2) is typically the major component of the total gas fraction; however, other gases such as hydrogen sulphide, nitrogen and methane can be present. Together, these gases have the potential to contribute to global CO_2 emissions, or smaller polluting effects such as acid rain. However, these emissions are minimal when compared to those produced by fossil fuel combustion. When dissolved or released to the environment via waste water, geothermal effluent can contribute to the unwanted growth of weeds or unwanted growth of bacteria, limiting the production capacity of aquatic species.

ECONOMICS

Geothermal installations have the potential to displace other more costly and environmentally damaging technologies. Costs for geothermal installations have been falling and are becoming more competitive. Geothermal systems are capable of deployment in a very wide range of circumstances where their contribution is competitive in power generation, heat exchange (energy efficiency) and ultimately carbon credit and valuation.

There are, however, a range of risks and obstacles for the future development of both hydrothermal and EGS facilities: 1) Due to high risk and expensive financing charges, investment in many geothermal projects remains low. The exploratory phases of a geothermal project are marked by not only high capital costs but also a significant chance of failure. Risk reduction strategies, such as co-funding exploration wells, could provide incentive to industry to accept the risks associated with preliminary stages of a geothermal project. 2) Uncertainty of government funding has diminished ongoing research in drilling technology and mapping of geothermal resources, two critical aspects of geothermal energy. As with all energy projects, certainty is important for projects that take an average of ten years to move from exploration to generation. 3) Grid Access restricts some of the most promising geothermal resources that lie great distances from regions of large electricity consumption. The need to install adequate transmission capacity often deters investment in geothermal projects, thus impeding the development of this renewable energy. 4) Canada has no current production tax credit for geothermal facilities. It is clear that a long-term geothermal production tax credit can provide significant benefits, particularly in reducing the uncertainty currently associated with public funding.

RESEARCH NEEDS

1. Development of a national geothermal database – voluminous data exist that would add reduction of geological risk during geothermal exploration if this information were available in a coherent database. These data have been collected for various reasons and, as such, reside in dispersed locations, or remain in non-digital form. Combining existing digital data from multiple sources and digitizing is needed.

2. New combined field, laboratory and computer modeling investigations are needed to fill data gaps. Most of Canada has no geothermal information, and in many regions where information exisits, the data are insufficient to characterise geothermal resources.

3. Re-establish capacity to conduct fundamental and applied research for both high and low temperature geothermal exploration. There has been a significant loss of capacity for laboratory analyses of geothermal properties (e.g. heat generation, thermal conductivity).

4. New fundamental research to understand controls on deep crustal hydrogeology, stress fields and geothermal properties. A network of research wells could greatly increase Canada's competitive advantage in development of geothermal technology along with enhancing knowledge of the geologic framework of high potential geothermal areas.

5. Geoscience knowledge to add development of a geothermal regulatory framework that would ensure long-term sustainable production of resources with minimal environmental impact.

6. Fundamental research to facilitate EGS development. This would include work on the regional stress field, hydrofracking, microseismic monitoring, and more efficient and inexpensive exploration methods.

7. Pilot projects to help develop economic geothermal resources in Canada while also supporting research and training of highly qualified personnel in Canada.

1. INTRODUCTION

Concerns over climate impacts of carbon based fuel emissions (IPCC, 2007), projected exponential growth in energy demand (IEA, 2009), as well as debate over long term supplies of conventional oil, have lead to growing interests in increasing renewable and clean energy supplies. A switch to more renewable energy will likely involve using numerous resources such as solar, wind, hydro and geothermal. Of these geothermal energy has several advantages that make it an attractive energy resource. The first is its very high capacity factor (actual output versus generation potential) relative to other renewables. This allows geothermal to provide reliable baseload energy supply for electrical generation (Fig. 1.1). Globally, geothermal energy has also shown to be a cost-competitive source of energy (Fig. 1.2). Along with its low carbon footprint and minimal environmental impact, there is thus great potential for geothermal energy to become a significant contributor to the global energy market (Fridleifsson, 2001).

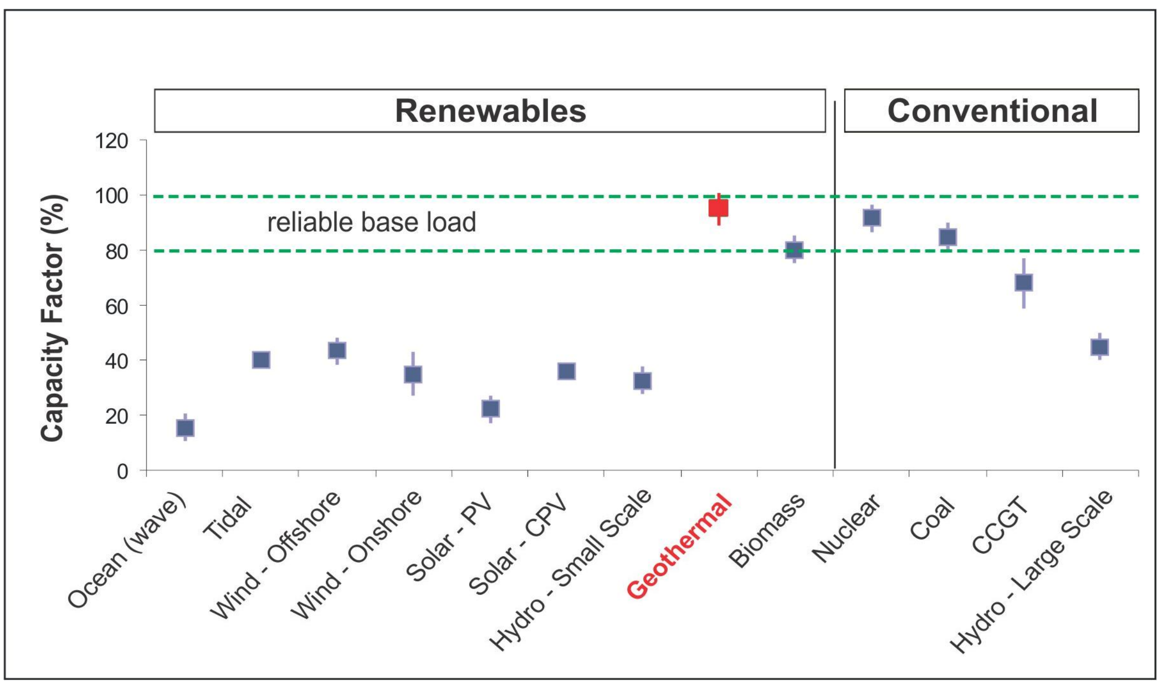


Figure 1.1. Typical capacity factors of different power generation technologies
Source: Emerging Energy Research (2009). PV = photovoltaics, CPV = concentrated photovoltaics, CCGT = combined-cycle gas turbine.

Geothermal energy production has shown global increase and for some countries it now forms a significant proportion of electrical supply. In the US alone, electricity generation from geothermal sources totalled 2,564 MWe (or 18,000 GWh) at end of 2005, making the US the leader in total geothermal energy production (WEC, 2007). As of October 2009, this number grew to a total installed capacity of 3,153 MW with a 26% annual growth rate for new projects (Jennejohn, 2010). The 188 projects currently underway in the US are expected to provide another 7,000 MW of baseload power capacity to 15 states, feeding the energy demands of approximately 7.6 million people and replacing the total power used by coal-fired power plants in California (Jennejohn, 2010). Current geothermal energy production in the US already displaces consumption of 60 million barrels of oil/year (~29 million tonnes CO_2 emissions/year).

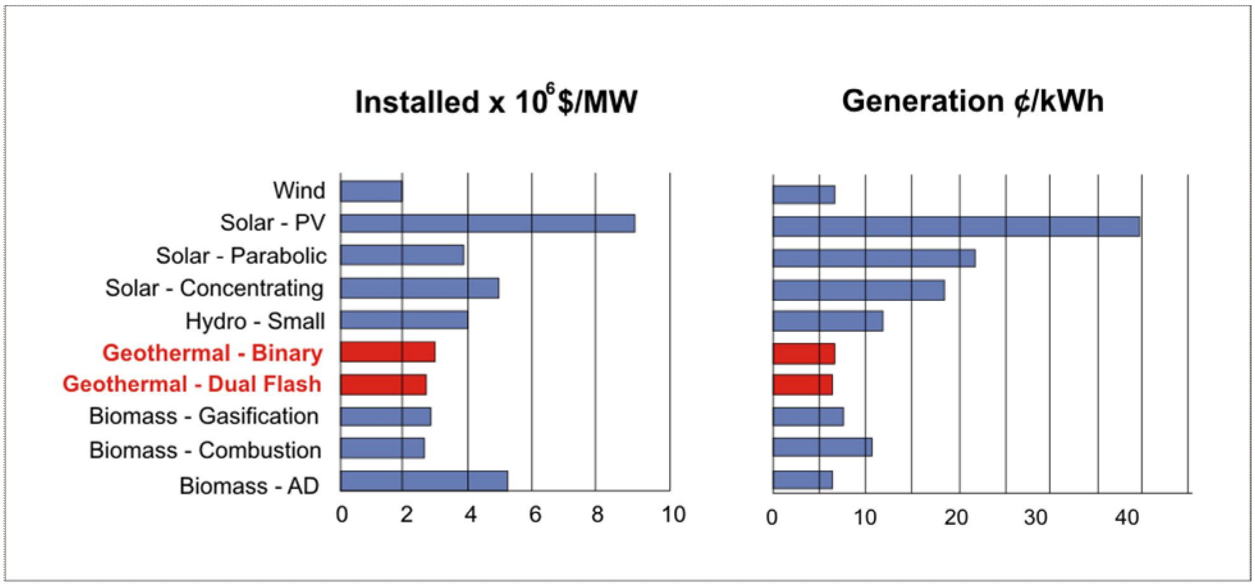


Figure 1.2. Comparison of installation and generation costs for various renewable energy resources. Source: California Energy Commission 2007.

While geothermal energy has been developed extensively in the US and other regions of the World, it has not been taken advantage of in Canada (Table 1). Currently there is no electrical generating capacity in Canada, however, based on the last estimate in 2010 there is 1126 MWt or 2010 GWh of direct use installed. Shallow heat exchange systems are rapidly gaining interest in Canada, growing at an annual rate of 10-15% since 2000 (Lund et al., 2005) and recently as high as 50% (Lund, 2010). There were an estimated 55,000 geoexchange units installed in Canada in 2010 (Thompson, 2010). This compares to a global installed capacity of nearly 76,000 GWh of direct use and a global annual growth rate of 10% in approximately 70 countries (Lund et al. 2005). More than half of this energy was used for space heating, and another third for heated pools. The remainder supported industrial and agricultural applications (Lund et al., 2005).

Table 1. Geothermal energy utilization in 2010 for the top ten countries in the world and Canada

Electricity Production		**Direct Use**	
	In GWh electric		In GWh thermal
United States	16,603	China	20,932
Philippines	10,311	United States	15,710
Indonesia	9,600	Sweden	12,585
Mexico	7,047	Turkey	10,247
Italy	5,520	Japan	7,139
Iceland	4,597	Norway	7,001
New Zealand	4,055	Iceland	6,768
Japan	3,064	Italy	2,762
Kenya	1,430	Hungary	2,713
El Salvador	1,422	Canada	2,465
Sum of Top 10	63,649	Sum of top 10	88,322
Canada	0	Canada	2,465
All other	3,597	All Other	33,375
World Total	**67,246**	**World Total**	**121,696**

Source: Lund et al. (2010)

The now defunct National Geothermal Program (a Canadian government research program that ended in 1986) demonstrated that Canada has a geological environment favourable to geothermal development (Jessop, 2008a, 2008b)(Chapter 3). This program defined high temperature resources suitable for geothermal exploration and development, particularly in British Columbia, Yukon and the Northwest Territories. Medium and low temperature geothermal resources were also defined within sedimentary basins and abandoned mines throughout Canada. Pilot projects drilled at Meager Creek, British Columbia and Regina, Saskatchewan further proved that geothermal power production in Canada is feasible. Now 25 years since the program ended advancements in technologies have further increased the economic potential of these geothermal resources. The intent of this report is to review the current knowledge base of geothermal resources in Canada, and the potential for it to become a significant source of renewable clean energy in the future.

1.1 WHAT IS GEOTHERMAL ENERGY?

Geothermal energy is derived from heat in the Earth's interior. The Earth's heat is generated dominantly by radioactive decay of three key elements (Uranium, Thorium, and Potassium), in addition to primordial heat related to the original formation of the planet (Fig. 1.3). This internal heat flows naturally to the surface by conduction and creates a gradient where temperature of the solid earth rises with increasing depth (Fig. 1.4). In theory, geothermal energy potential is present below the entire surface of the Earth. In practice however, special geologic conditions are required for geothermal energy to be economically exploited. These are described in more detail in Chapter 2.

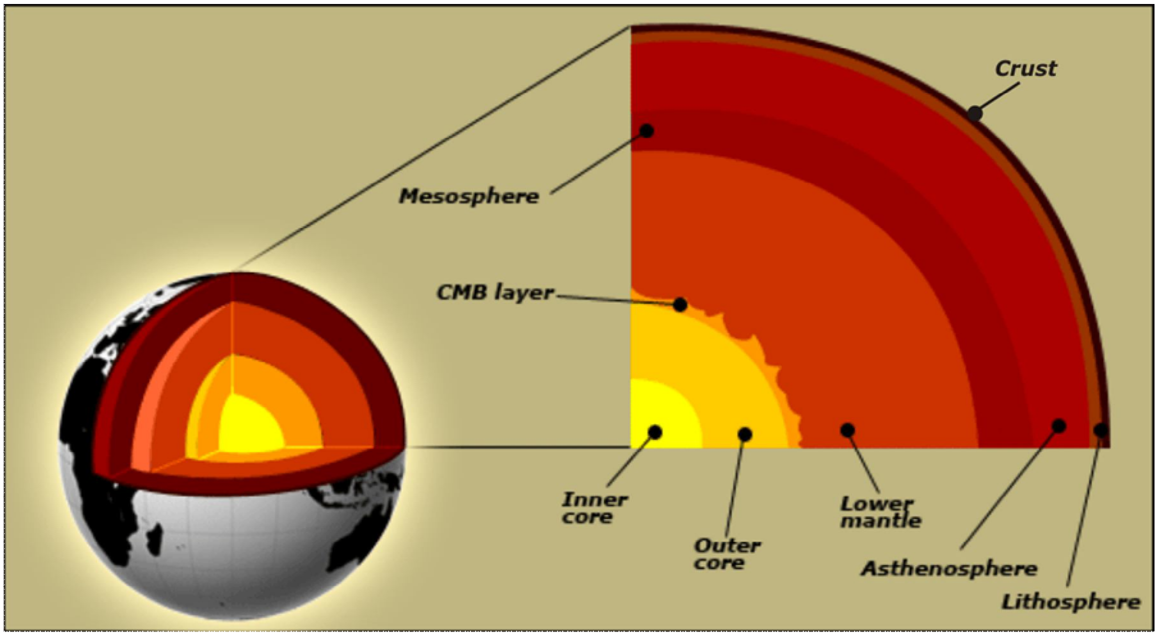


Figure 1.3. Heat generated by radio active decay flows outward from the Earth's interior. The crust insulates the Earth's interior heat creating a geothermal gradient where temperatures increase with depth. (from GEO, 2000).

For a geothermal resource to become an economic supply of energy, three main factors are required: 1) high temperature rocks within economic and technological drilling depths, 2) a carrier fluid that can transport heat energy to the surface, and 3) a permeable pathway through hot rocks that the carrier fluid can move through. While these represent underlying geological controls on the economic feasibility of geothermal development, technology is progressively reducing these barriers. New technology is increasing drilling depths, enhancing the ability to induce flow systems through rocks where the natural permeability is too low, and lowering the temperature of the resource required to generate electricity.

This has progressively increased feasible depths to produce geothermal power and broadened the geological conditions in which geothermal development is possible. In addition, new heat exchange technology has progressively lowered the temperature of a resource required to produce electricity. These advancements have significantly increased the geologic environments where geothermal resources may be developed.

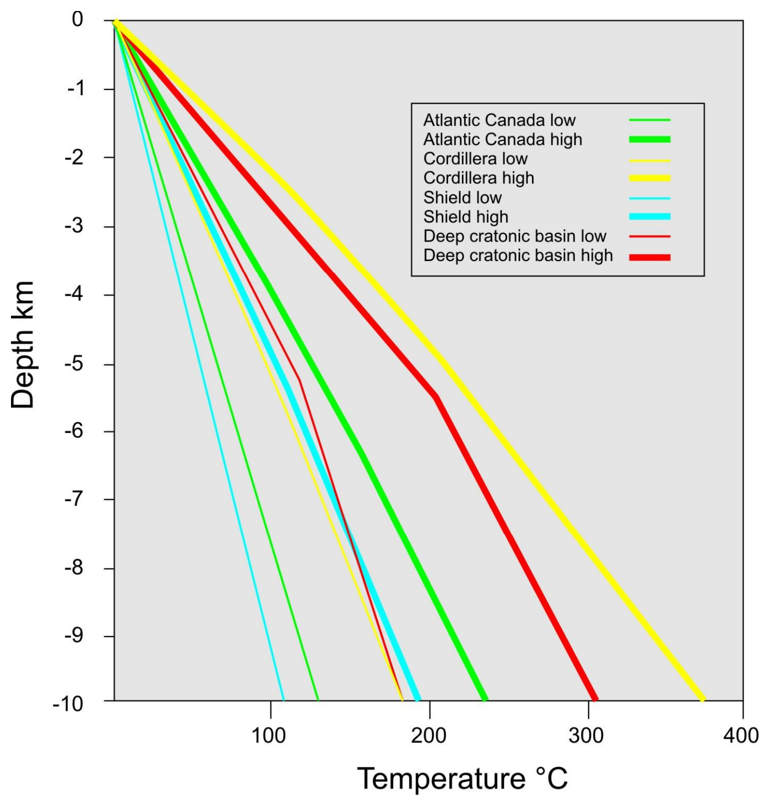


Figure 1.4. Example estimated high and low range thermal gradients for different geological provinces across Canada (Modified from Majorowicz and Grasby, 2010a). Temperatures increase progressively with depth.

2. GEOTHERMAL RESOURCE TYPES

2.1 INTRODUCTION

Geothermal resources range from shallow rock and sediments saturated with groundwater, to hot water and rock several kilometres below the Earth's surface. Geothermal resources are thus often broadly categorized into three types, although the temperature ranges differ depending on publication source: high-temperature (typically greater than 150 °C), medium-temperature (80 °C to 150 °C), and low-temperature (less than 80 °C). The temperature of the resource produced influences both the technology required for development and the potential end use. High and medium temperature resources are readily used for electrical generation, whereas low temperature resources can only be used for direct heating or other similar applications. An overview of these key resource types and the geological environments where they may be found are presented here.

The origin of geothermal energy is linked with the internal structure of the Earth and the physical processes occurring there (Barbier, 2002). Heat is moved through much of the Earth via convection, but conduction appears to be the dominant means by which it is transported through the crust (Beardsmore, 2001). Conductive heat flow has been measured over much of the Earth's surface and a recent compilation of 20,201 data points (Pollack et al., 1993) suggested a global mean of 87± 2 mWm^2, with a total heat loss of 44.2 ± 1.0 x 10^{12} W. Heat loss is by no means evenly distributed, however, with average heat loss through the oceans being considerably higher than through the continents. Continental heat flow is derived from radiogenic decay within the upper crust, together with the heat generated in the most recent local magmatic episode and the heat coming from the mantle (Barbier, 2002). In the oceanic crust, the concentration of radioactive isotopes is so low that radiogenic heating is negligible, and the heat flow is largely derived from heat flowing from the mantle below the lithosphere (Barbier, 2002). Except for anomalous locations of mid-ocean ridge volcanoes (e.g. Iceland), or volcanic hot spots (e.g. Hawaii) geothermal energy resources on the oceanic crust are limited. Thus, principal factors that may play a role in the concentration of heat in the crust are: 1) the abundance of radioactive elements, 2) the ability of rock to conduct heat (thermal conductivity), and 3) active tectonic, volcanic, or hydrogeological processes that can localise high heat flow in the area.

2.2 HIGH-TEMPERATURE GEOTHERMAL ENERGY

High-temperature geothermal resources are generally found in areas where there is a high geothermal gradient[1] and, consequently, where the Earth's crust receives greater heat flow than surrounding areas, in other words, in areas where there is a thermal anomaly. These areas of anomalously high heat flow are often confined to areas on the boundaries between tectonic plates (convergent and divergent boundaries) (Muffler, 1976). In Canada, high-temperature geothermal resources are associated with the Western Canadian Volcanic Belt (e.g., Lewis et al., 1992). It is not uncommon to find other evidence of geothermal activity in these areas, such as hot springs, steam vents and geysers. These high heat flow areas generate heat that warms the water contained in permeable reservoirs adjacent to it, via thermal conduction (Barbier, 2002). The local heat source could be a magma body at 600–1000°C, intruded within a few kilometres of the surface. However, geothermal fields can also form in regions unaffected by recent (Quaternary age) shallow magmatic intrusions. The anomalous high heat flow may be due to particular tectonic situations, for example, to thinning of the continental crust, which implies the upwelling of the crust-mantle boundary and consequently higher temperatures at shallower depths (Barbier, 2002).

In order to have a productive geothermal resource, however, more than a thermal anomaly is needed. A reservoir, or aquifer, which is a sufficiently large body of permeable rocks at a depth accessible by drilling is also required. This body of rock must contain large amounts of fluids (water or steam), which can carry heat to the surface. The origin of these thermal fluids is primarily meteoric water, which infiltrates into the recharge areas at the surface and descends to depth, increasing in temperature while penetrating the hot rocks of the reservoir. Water moves inside the reservoir by convection, due to density variations caused by temperature, transferring heat from the lowest parts of the reservoir to its upper parts to create a reservoir of fairly uniform temperature (Barbier, 2002). Heat is transferred by conduction towards the permeable reservoir rocks, which contain the fluids. Hot fluids often escape

[1] The average gradient within a few km's of the Earth Surface is about 30 °C/km, but values as low as about 10°C/km are found in ancient continental crust and very high values (>100 °C/km) are found in areas of active volcanism.

from the reservoir and reach the surface, producing the visible geothermal activity described above. Such movement of hydrothermal fluids through the deep crust will be significantly influenced by regional stress fields and associated fracture networks (Chapter 9).

High temperature geothermal systems can be classified into many different categories and subcategories. The systems predominantly exploited today are water- and vapour-dominated hydrothermal systems, hot dry rock (HDR), and geopressured and magmatic geothermal systems, which show potential for industrial exploitation with future technological advances. Enhanced geothermal systems, whereby HDR resources are 'enhanced', are a newer technology involving hydraulic stimulation to create an effective subsurface heat exchanger.

2.2.1 Hydrothermal Systems

Hydrothermal systems (or geothermal reservoirs, or fields) are traditionally classified as water-dominated or vapour-dominated, the latter having a higher energy content per unit fluid mass (Barbier, 2002). Water-dominated fields are further divided into hot water fields, producing hot water, and fields producing mixtures of water and steam, called wet steam fields. Of the approximately 100 hydrothermal systems that have been investigated, less than 10% are vapour-dominated, 60% are wet steam fields (water-dominated), and 30% produce hot water (Hochstein, 1990). The most efficient and economic use for geothermal energy is electricity generation, which is derived predominantly from high temperature geothermal systems related to hydrothermal systems.

2.2.1a Water-dominated hydrothermal systems

Hot water fields are capable of producing hot water at the surface at temperatures up to 100 °C. The reservoir (aquifer) is typically overlain by confining layers that keep the hot water under pressure (Fig. 2.1). Temperatures in the reservoir remain below the boiling point of water at any pressure because the heat source is not large enough (Barbier, 2002). These fields may also occur in areas with normal heat flow (Barbier, 2002). On the surface there are often thermal springs whose temperatures are, in some cases, near the boiling point of water.

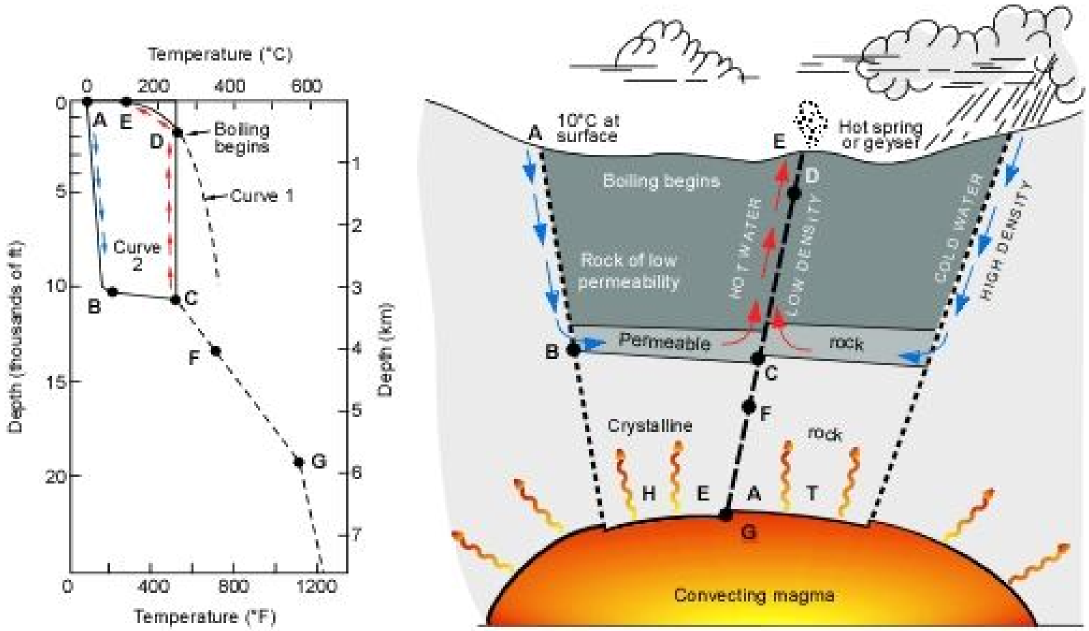


Figure 2.1 Model of a geothermal system. Convection, by its nature, tends to increase temperatures in the upper part of a system as temperatures in the lower part decrease. Curve 1(left figure) is the reference curve for the boiling point of pure water. Curve 2 (left figure) shows the temperature profile along a typical circulation route from recharge at point A to discharge at point E (right figure). Source: White (1973).

A hot water hydrothermal field is of economic interest if the reservoir is found at a depth of less than 2 kilometres, if the salt content of the water is lower than 60 g/kg, and if the wells have high flow-rates (above 150 tons/hour) (Barbier, 2002). The best known examples of exploited hot water fields are those of the Pannonian basin (Hungary), the Paris basin (France), the Aquitanian basin (France), many Russian fields, the Po river valley (Italy), Klamath Falls (Oregon, USA), and in Tianjin (China) (Barbier, 2002).

Wet steam fields contain pressurised water at temperatures exceeding 100 °C and small quantities of steam in the shallower, lower pressure parts of the reservoir. The liquid phase, which is the dominant phase in the reservoir, controls the pressure inside the reservoir (Barbier, 2002). Steam is not uniformly present, but rather occurs in the form of bubbles surrounded by liquid water, and does not noticeably affect fluid pressure. An impermeable confining layer generally exists to prevent the fluid from escaping to the surface, thus keeping it under pressure. When the fluid is brought to the surface via a well and its pressure decreases, a fraction of the fluid is flashed to steam, while the greater part remains as boiling water (Barbier, 2002). The water-steam ratio varies from field to field, and even from one well to the next within the same field (Barbier, 2002). In many cases only steam is used to produce electrical energy, therefore liquid water must be removed at the surface in special separators. More than 90% of the hydrothermal reservoirs exploited on an industrial scale are of the wet steam type. Electricity generation is their optimal utilisation.

The surface manifestations of these fields include boiling springs and geysers. The heat source is large and generally of magmatic origin. The water produced contains chemical constituents commonly found in groundwater (e.g. chlorides, bicarbonates, sulphates, borates, fluorides and silica), but the concentrations are very large (from 1 to over 100 g/kg of fluid, in some fields up to 350 g/kg), thus potentially causing severe scaling problems to pipelines and plants. However, progress is being made to address this issue with a variety of techniques (Gallup, 2009). One important economic aspect of wet steam fields is the large quantity of water extracted with the steam (e.g. 6600 tons/hour at Cerro Prieto, Mexico) (Barbier, 2002). Owing to its generally high chemical content this water has to be disposed of through reinjection wells drilled at the margins of the reservoir. Examples of wet steam fields producing electricity are (Barbier, 2002): Cerro Prieto, Los Azufres and Los Humeros (Mexico), Momotombo (Nicaragua), Ahuachapa´n-Chipilapa (El Salvador), Miravalles (Costa Rica), Zunil (Guatemala), Wairakei, Ohaaki and Kawerau (New Zealand), Salton Sea, Coso and Casa Diablo (California), Puna (Hawaii), Soda Lake, Steamboat and Brady Hot Springs (Nevada), Cove Fort (Utah), Dieng and Salak (Indonesia), Mak-Ban, Tiwi, Tongonan, Palinpinon and Bac Man (Philippines), Pauzhetskaya and Mutnovsky (Russia), Fang (Thailand), Kakkonda, Hatchobaru and Mori (Japan), Olkaria (Kenya), Krafla (Iceland), Azores (Portugal), Kizildere (Turkey), Latera (Italy), and Milos (Greece).

2.2.1b Vapour-Dominated Hydrothermal Systems

Vapour-dominated fields produce dry saturated or slightly superheated steam at pressures above atmospheric. They are geologically similar to wet steam fields, but the heat transfer from depth is much higher (Barbier, 2002). Research suggests that their permeability is lower than in wet steam fields, and the presence of an impermeable confining layer is of fundamental importance. Water and steam co-exist, but steam is the continuous predominant phase, regulating the pressure in the reservoir: the pressure is practically constant throughout the reservoir (Barbier, 2002). These fields are called dry or superheated fields. Produced steam is generally superheated, with small quantities of other gases, mainly CO_2 and H_2S. When a well penetrates the reservoir and production begins, a depressurised zone forms at the well-bottom. This pressure drop produces boiling and vaporisation of the liquid water in the surrounding rock mass. A dry area, i.e. without liquid water, forms near the well-bottom and steam flows through this zone. Steam crossing the dry area starts to expand and cool, but the addition of heat from the very hot surrounding rocks keeps steam temperature above the vaporisation value for the pressure at that point. As a result, the well produces superheated steam with a degree of superheating that may reach 100 °C, for example with wellhead pressures of 5 to 10 bar (0.5 to 1 MPa) and a steam outlet temperature of more than 200 °C (Barbier, 2002).

Surface geothermal activity associated with vapour-dominated fields, whether dry or superheated, is similar to the activity present in wet steam fields. About half of the geothermal electric energy generated in the world comes from six vapour-dominated fields: Larderello (Italy), Mt. Amiata, (Italy), The Geysers (California), Matsukawa (Japan), Kamojang and Darajat (Indonesia).

2.2.1c Production and Sustainability of the Resource

Based on the three dominant types of systems described above, there are three types of power plants operating today:

- **Binary-cycle plants**, which pass moderately hot geothermal water by a secondary fluid with a much lower boiling point than water. This causes the secondary fluid to flash to vapour, which then drives the turbines (hot water fields);
- **Flash steam plants**, which pull deep, high-pressure hot water into lower-pressure tanks and use the resulting flashed steam to drive turbines (wet stream fields); and
- **Dry steam plants**, which directly use geothermal steam to turn turbines (vapour-dominated fields).

While geothermal energy is seen as a renewable energy resource, if not managed properly on the time scale normally used in human society, geothermal resources may not be, strictly speaking, renewable. They are renewable only if the heat extraction rate does not exceed the reservoir replenishment rate. Exploitation through wells, sometimes using downhole pumps in the case of non-electrical uses, leads to the extraction of very large quantities of fluid and, consequently, to a reduction or depletion of the geothermal resource in place. Shut-in pressures measured at the wellhead always decline with time as a consequence of fluid extraction and depletion of the reservoir (Barbier, 2002). Disposal of the spent cooled fluid after use is thus also an important operation in each geothermal application (Chapter 10). In electrical uses, steam condenses into water that is often rich in salts, and this polluting waste must be disposed of accordingly. More than 95% of the fluid produced is often reinjected into the reservoir as water, limiting pressure losses and replacing at least part of the fluid extracted. The key to a successful geothermal project is to ensure, by careful reservoir evaluation and monitoring, that the geothermal reservoir will last for the lifetime of the geothermal installations. Experience has taught us that good reservoir management practices can assure an adequate steam supply for many decades (Barbier, 2002).

2.2.2 Enhanced Geothermal Systems (EGS) / Hot Dry Rock (HDR)

Enhanced Geothermal Systems (EGS) are a new type of geothermal power technology that do not require natural convective hydrothermal resources. Until recently, geothermal power systems have only exploited resources where naturally occurring water, rock porosity and permeability are sufficient to carry heat to the surface. However, the vast majority of geothermal energy within drilling reach is in dry and non-porous rock. EGS technologies "enhance" and/or create geothermal resources in this **hot dry rock (HDR)** through hydraulic stimulation.

By far, the largest portion of the world's geothermal resources reside in rock that is hot but is not naturally in contact with a fluid that can be used to transport that heat to the surface for use. The thermal energy content of such hot dry rock (HDR) found at accessible depths has been estimated to be on the order of 10 million quads (1 quad = 10^{15} BTU = 1.06 X 10^{18} Joules) (Edwards et al., 1982). These resources occur in areas of high heat flow and provide sites for the early development and application of the technology to extract useful energy from HDR and, if commercially developed, could in themselves make HDR energy a major contributor to a clean-energy world in the 21st century (MIT, 2006).

In this technique, water is pumped (via a well) into a known formation of hot rock (Duchane, 1996). The hydraulic fracturing, achieved by pumping water into the well at high pressure, forces open tiny pre-existing fractures in the rock, creating a system or "cloud" of fractures that extends for tens of metres around the well (Fig. 2.2). Seismic techniques are used to follow the growth of the reservoir, to assess its location, and to determine its approximate dimensions. The body of rock containing the fracture system acts as the heat reservoir. The fracture system allows water to contact a large area of rock surface in order to absorb the heat and bring it to the surface. This “engineered geothermal reservoir” acts as any natural geothermal reservoir would, with a small amount of water dispersed in a large volume of hot rock (Duchane, 1996).

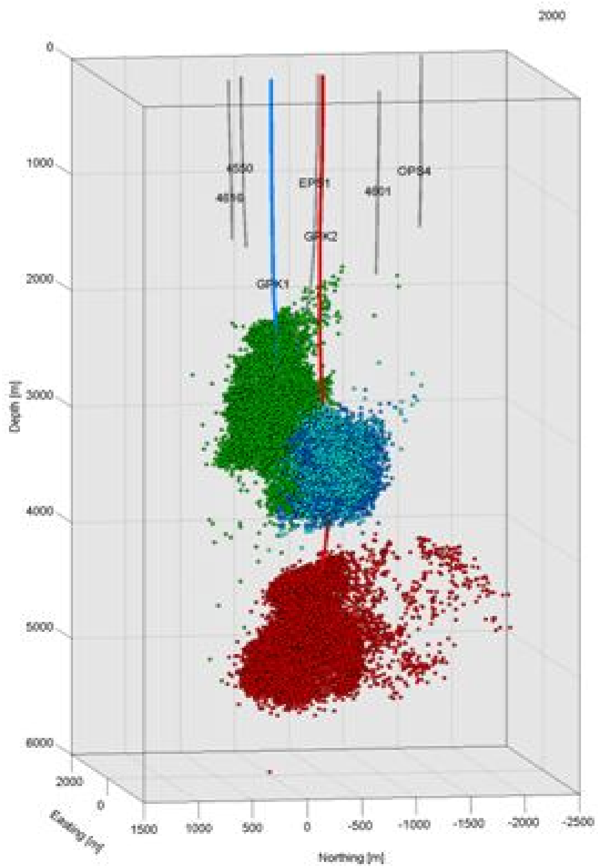


Figure 2.2. Microseismic cloud formed by hydraulic fracturing of an EGS well. Source: Majer et al. (2007)

Using the seismic data as a guide, one or more production wells are subsequently drilled into the engineered reservoir at some distance from the first well (Fig. 2.3). Water is circulated down the injection well(s) and through the fractured HDR reservoir, which acts as a heat exchanger. The fluid then returns to the surface through the production well(s), and thus transfers the heat to the surface as steam or hot water, which is converted into electricity using either a steam turbine or a binary power plant system. All of the water, now cooled, is injected back into the ground to heat up again in a closed loop. In a properly engineered HDR reservoir, there are a number of fluid-flow pathways between the injection and production wellbores (Duchane 1996). Due to the constant pressure introduced by the injection well, the circulation within the reservoir will depend entirely on the extraction rate from the production wells, creating a reliable energy resource (Duchane 1996).

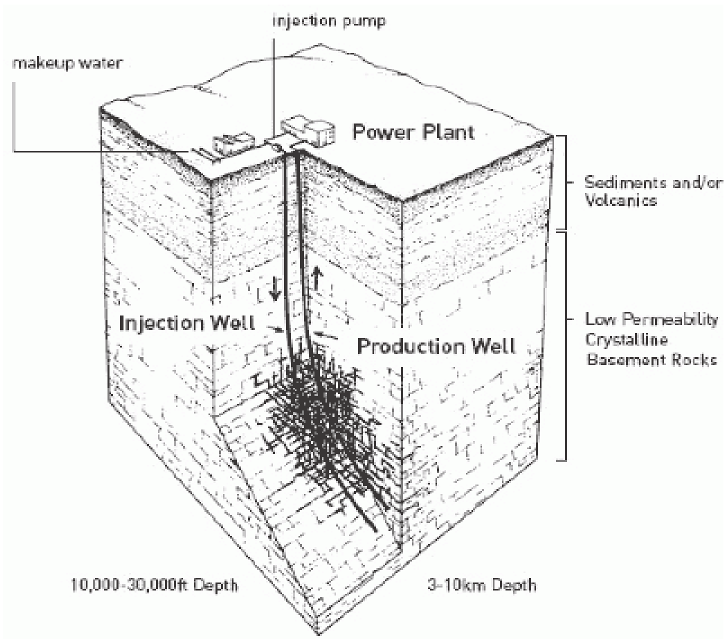


Figure 2.3. Schematic of a conceptual two-well Enhanced Geothermal System in hot rock of a low-permeability crystalline basement (Source: MIT, 2006). Injector and producer wells are shown, along with the man-made fractures in the rock at depth between the wells. The injected fluid is pushed from injector to producer all the while picking up heat from the rock.

There are HDR/ EGS systems currently being developed and tested in France, Australia, Japan, Germany, the US, Switzerland and the UK. The largest EGS project in the world is currently being developed in the Cooper Basin, Australia — with the potential to generate 5,000–10,000 MW. The possibility of using CO_2 as a working fluid and including carbon sequestration as a component of geothermal energy projects is also currently being investigated (Pruess, 2006).

2.2.3 Magma Energy

The thermal energy stored in magma bodies represents a huge potential resource (Barbier, 2002). In the US, the Magma Energy Extraction Program aimed to determine the engineering feasibility of locating, accessing, and utilising magma as a viable energy resource. Research is also being carried out in Japan (Tomiya, 2000).

Realisation of this objective would require progress in four critical areas. These are (Dunn, 1988):

- **magma location and definition**: crustal magma bodies must be located and defined in enough detail to position the drilling rig;
- **high-temperature drilling and completion technology** require development for entry into magma;
- **engineering materials** selected and tested for compatibility with the magmatic environment; and;
- **heat extraction technology** needs to be developed to produce energy extraction rates sufficient to justify the cost of drilling wells into the magma bodies.

2.3 LOW- TO MEDIUM-TEMPERATURE GEOTHERMAL ENERGY

Much of the attention worldwide for geothermal energy development has traditionally focused on the generation of electricity and, to a lesser extent, the potential exploitation of hot water in deep sedimentary basins for direct space heating. Although not very efficient, electricity generation is feasible at lower temperatures than those described above. In recent years there has been increasing interest in the use of moderate (80 °C to 150 °C) to low (<80 ^{o}C) temperature resources for heating and direct cooling applications.

2.3.1 Electricity Generation

If the temperature of the geothermal reservoir is above 80 °C (medium-temperature), electricity can still be generated by means of a binary cycle plant (Fig. 2.4) (DiPippo, 2004). In this technique, a second liquid with a low boiling point is “flashed” or vapourised by the geothermal heat in a heat exchanger. As this vapour expands and rises, it passes through a turbine coupled to a generator (turbo-alternator) (Barbier, 2002). After having passed through the turbine, the vapour is condensed and recycled back to the heat exchanger. The efficiency of these systems is low (less than 6% (Barbier, 2002)) because binary plants are poor converters of heat into work, although some plants have achieved an efficiency of more than 40% (DiPippo, 2004). Despite these low efficiencies, binary power plant technology has emerged in the global market as a low-cost and reliable means of electricity generation from medium-temperature reservoirs (Barbier, 2002; Bertani, 2005).

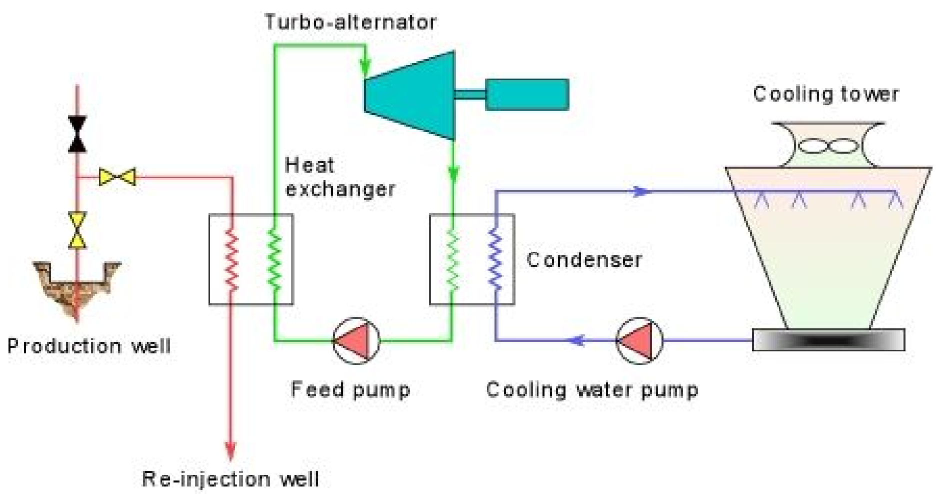


Figure 2.4. Basic schematic of a binary (organic-rankine cycle) power plant. Source: Dickson and Fanelli (2004).

2.3.2 Geopressured Reservoirs

Deep sedimentary basins have been identified throughout the world as potential targets for the exploration of geothermal resources primarily because of the presence of significant quantities of groundwater contained within them. Even with an average geothermal gradient of 25 °C/km, groundwater at a depth of only 2,000 m can attain a temperature of 50 °C. Higher temperatures can be expected if the geothermal gradient is above average or at greater depths within the basin. Temperature of these deep basin groundwaters can exceed 80 °C, and in some areas well over 100 °C, and have been used successfully to generate electricity from hot waters co-produced from petroleum wells. Generally though, these high temperature waters are less common in sedimentary basins. Geopressured reservoirs can contain pressurised hot water (up to 100% in excess of the hydrostatic pressure corresponding to that depth) (Barbier, 2002). As such, these geopressured fields could produce not only the thermal energy of the pressurised hot water, but also hydraulic energy, by virtue of the very high pressure (Eaton, 1990; Barbier, 2002). These energy forms can also be converted to higher value forms of energy using available technologies. Thermal energy can be converted to electricity in a geothermal turbine, and hydraulic energy can be converted to electricity using a hydraulic turbine. Dissolved methane gas, commonly found in association with geopressured reservoirs, can be separated and sold, burned, compressed, liquefied, converted to methanol, or converted to electricity by fuelling a turbine. However, at this point there are no commercial developments of this type (Gallup, 2009). Geopressured resources have been investigated extensively in offshore wells in Texas and Louisiana in the US Gulf Coast area (deepest well 6,567 m), and pilot projects were operated there for some years to produce geopressured fluid and extract its heat and methane gas content (Eaton, 1990).

More commonly, however, these moderate to high temperature groundwater resources can be utilised for direct heating applications, such as space heating of buildings and greenhouses, industrial processes, drying of agricultural products, aquaculture, and thermal spas and pools. For example, Jessop (1976) described development of 60 °C groundwater resources for space heating of apartment buildings in the Paris Basin of France. Higher water temperatures provide more heat energy per volume of water extracted, which can affect the economics of a project.

2.3.3 Direct Use and Geo-Exchange Systems

Use of warm or hot water directly is commonly referred to as **direct use geothermal energy**. Ghomshei and Sadler-Brown (1996) reviewed direct use geothermal applications in British Columbia, listing space heating, agriculture (greenhouses), aquaculture, recreation (spas), medical (balneology), and industrial use (process heating) as the dominant uses. Globally, the most predominant direct use is for geothermal heat pumps and the second largest for bathing and swimming (Fig. 2.5).

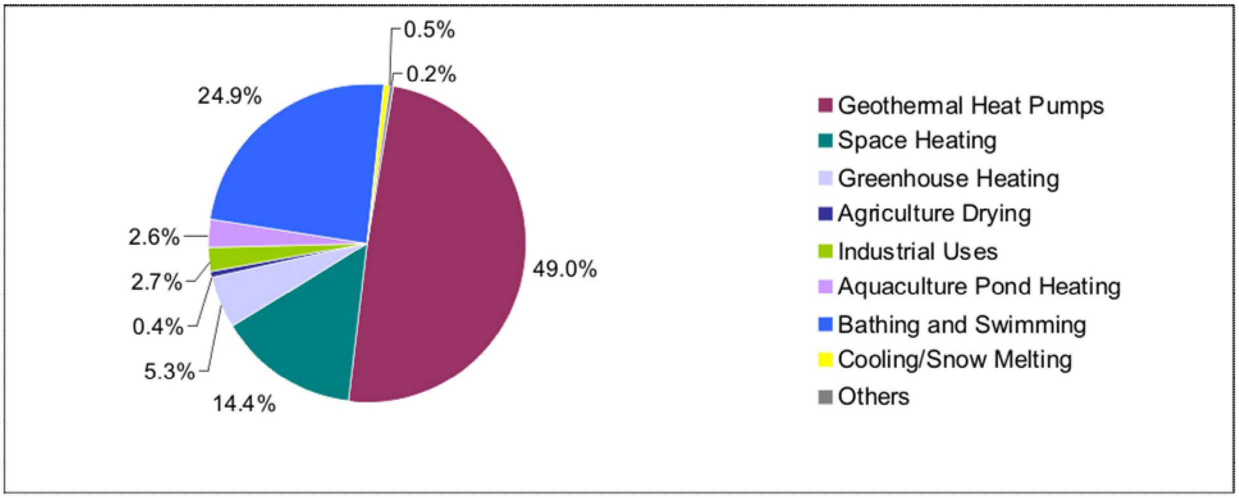


Figure 2.5. Direct applications of geothermal world wide (distributed by percentage of total energy use). Source: Lund et al. (2010).

Low temperature geothermal resources occur everywhere in the shallow subsurface, where mean annual ground temperatures are roughly 3 to 5 °C above the mean annual air temperatures. Temperature increases with depth in accordance with the local geothermal gradient, but is still relatively low even at a depth of a few hundred metres. In Canada, shallow ground (and hence, groundwater) temperatures commonly range from 8 to 12 °C and remain relatively constant throughout the year, but are generally lower than normal room temperature (20 °C) (Majorowicz et al. 2009). Therefore, many low-temperature heating applications employ heat pumps to enhance energy recovery and make up the difference between ground temperature and room temperature. The lower ground temperatures also permit direct cooling applications in many instances, thereby considerably lowering electrical consumption for chillers and air conditioners. These types of systems fall under the category of geo-exchange systems.

Geo-exchange systems, whether used for heating or cooling, or a combination of both, are known under a variety of names, including ground source heat pump systems, ground-coupled systems, earth energy systems, or, where storage is involved, aquifer or borehole thermal energy storage systems. These geo-exchange systems operate either as open loop systems, in which groundwater is extracted using a water well and used for heating or cooling, or the more common closed loop systems, which involve no direct communication with the groundwater regime (Fig. 2.6). In closed loop systems, heat exchange occurs through a set of horizontally buried pipes (horizontal loop) or pipe circuits placed in a borehole (vertical loop). Various types of closed-loop systems are available and are largely dependent on the local terrain, soil properties, climate, or property area. In horizontal loop systems, pipes may be placed in trenches at 1-2 m depth with approximately 120 to 180 m of pipe required per ton of system capacity (OEE, 2009). If the property size is small, a slinky loop system may be used and reduces the horizontal surface area required by arranging the pipe in overlapping loops, forming a coiled shape. Where property size is further reduced or system capacity needs are greater, a vertical borehole typically drilled to a depth of 50-250 m may be required but is often 3-4 times more costly (CGC, 2009). Where accessible, a horizontal loop system may also be laid on the bottom of a nearby lake or pond (pond loop). Pond loops are the most cost-effective closed-loop system and use the heat storage capacity of the water to either absorb heat in the winter or extract heat in the summer (CGC, 2009).

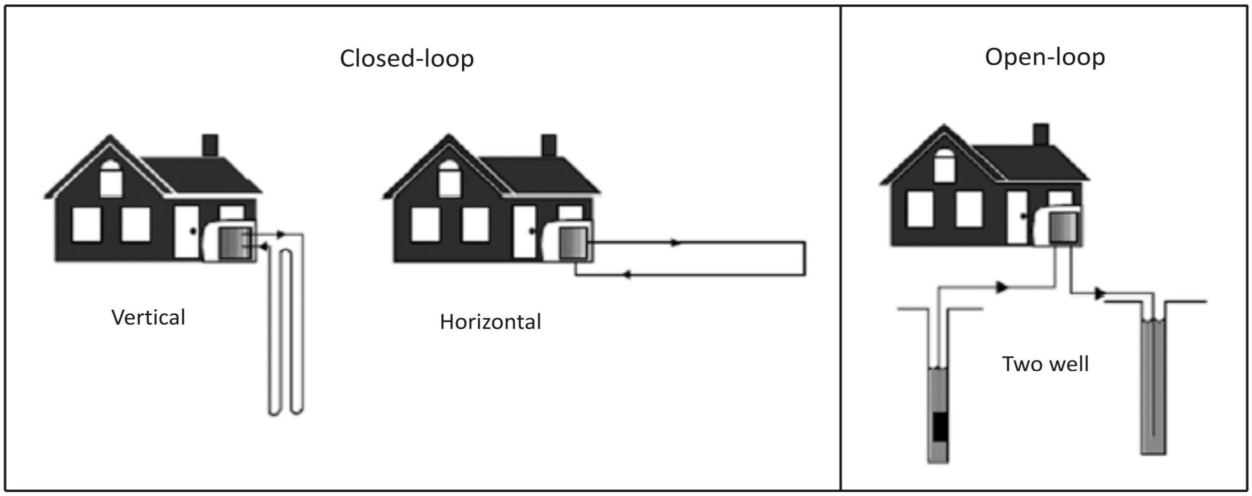


Figure 2.6. A basic schematic of the two main types of geoexchange systems: closed-loop and open-loop. Source: Lund et. al (2004).

Open loop geothermal systems extract groundwater from an aquifer via a well. The water is passed across a heat exchanger to allow transfer of energy for direct use in a building's heating / ventilation / air conditioning (HVAC) system, typically in combination with a heat pump. The majority of open loop systems subsequently dispose of the "used" groundwater either by discharging to a surface water body or injecting back into the aquifer. These types of open loop systems, known as pump-and-release or pump-and-dump systems, are relatively simple to implement and offer energy efficiencies comparable to closed loop systems at substantially reduced capital costs (Rafferty, 2001). However, these systems have potential for causing environmental degradation due to the long-term warming or cooling of the environment (e.g. Ferguson and Woodbury, 2004), as well as a degradation in system efficiency or system failure due to excessive warming (or cooling) of the aquifer (Bridger and Allen, 2005; Ferguson and Woodbury, 2005). This is particularly true in cases where injection of waste heat is not countered by removal of that heat at a later time, thus leading to heat build-up.

Alternatively, the subsurface can be considered as a potential store for heat (and cold) energy. Such thermal energy storage systems are becoming increasingly used for seasonal and longer-term storage of thermal energy. The forms of thermal mass storage include pit storage, rock-cavern storage, “closed loop” pipe, duct or borehole systems in unconsolidated materials or solid rock, and “open-loop” aquifer or gravel-water pit storage (Fig. 2.7). Closed-loop systems, including Borehole Thermal Energy Storage (BTES) systems, offer a good alternative when there are no suitable aquifers present at a site, or if the cost to determine the aquifer suitability and drill a well is large in comparison to the project budget. Open loop systems, including Aquifer Thermal Energy Storage (ATES) systems are best suited to aquifers, where enhanced permeability relative to solid rock provides adequate volumes of groundwater for heat exchange operation. Experience around the world with these various techniques has shown that with respect to the storage volume achievable, the ability to transfer energy, the temperature range, and the efficiency and cost, aquifer thermal energy storage (ATES) is one of the better methods of underground energy storage over longer time periods (IF Technology, 1995). Cavern Thermal Energy Storage (CTES) systems, which rely on ambient temperature groundwater stored in large caverns, have been developed at old mine sites in some areas around the world, including Springhill, Nova Scotia. Here, groundwater from the flooded coal mine workings has been used for heating and cooling of buildings since 1989 (Jessop et al., 1995). All three of these systems (ATES, BTES, and CTES) are being developed worldwide for heating and cooling applications, ranging from individual homes to large industrial and institutional complexes.

This report focuses primarily on geothermal resources for direct use of heat energy, rather than the full spectrum of geo-exchange applications as described above. However, in many regions, opportunities for combined heating and cooling may exist. Additional information on the broad types of geo-exchange systems is available through the Canadian GeoExchange Coalition (http://www.geo-exchange.ca/) and GeoExchangeBC (http://www.geoexchangebc.com/).

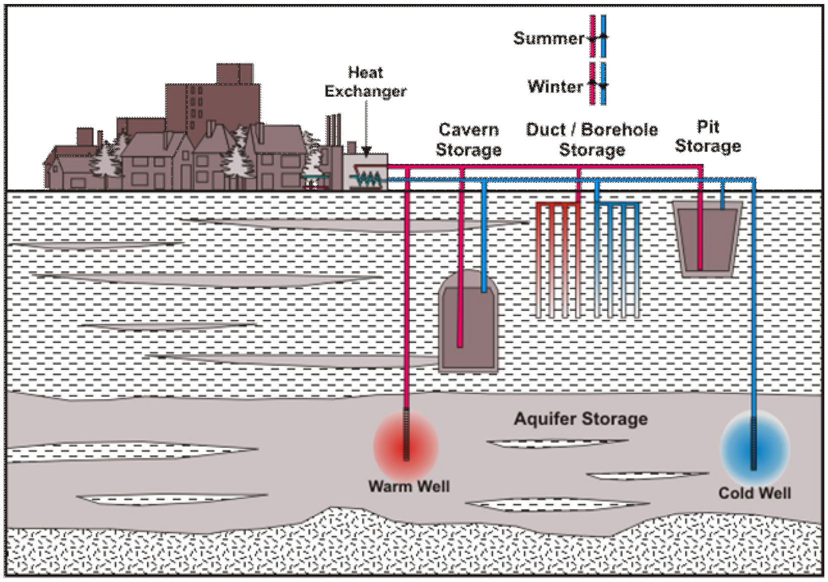


Figure 2.7. Various forms of underground thermal energy storage. Source: IF Technology (1995).

3. GEOTHERMAL SYSTEMS IN CANADA

3.1 INTRODUCTION

Canada has a broad range of geological provinces that greatly influence the range of potential for geothermal energy resources. Here we look at the three major geological regions: 1) the Canadian Cordillera representing the mountainous regions of western Canada, 2) sedimentary basins that represent broad regions of the country that are underlain by sedimentary rock, and 3) the Canadian Shield which extends through much of central and northern Canada. In general, terrestrial heat flow is highest throughout the Cordillera indicating a crust that is generally hotter than in older and more stable areas as represented by the Canadian Shield. Heat flow from sedimentary basins can be low but they also have low thermal conductivity which 'traps' much of that heat leading to high geothermal gradients. These basic factors and geological controls which govern the range of geothermal potential in Canada, are discussed in more detail below.

3.2 CANADIAN CORDILLERA

The Canadian Cordillera encompasses the mountainous region of western Canada that extends from the US border to the northern coast. The Cordillera developed in response to plate tectonic movements which drove the collision of island arcs or continental fragments into the western margin of ancestral North America, from Jurassic to Tertiary time (Coney et al. 1980; Monger et al. 1982; Parrish et al. 1988; Gabrielse 1985; Gabrielse and Yorath 1991). Compressional deformation ended abruptly in the southeastern Cordillera during the Late Paleocene. At this time, crustal-scale extensional faults formed with associated plutonism and volcanism (Armstrong 1988; Parrish et al. 1988; Gabrielse and Yorath 1991). From Eocene to Recent, the SW Cordillera has been affected by right-lateral strike-slip faulting (Gabrielse 1985).

The Cordillera is divided into five morphogeological belts (Fig. 3.1). These can be roughly defined as deformed sedimentary strata of either North American (Foreland Belt) or island-arc affinity (Insular and Intermontane Belts) that are separated by belts of plutonic and high-grade metamorphic rocks (Coast and Omineca Belts). The easternmost is the Foreland Belt, which consists of sedimentary rocks deposited on the passive margin of western North America during Paleozoic time, and which were folded, faulted and uplifted in Mesozoic time. The south end of the Rocky Mountains is roughly 200 km across, but in the north the Foreland Belt transitions into the wider McKenzie Mountains. The Omineca Belt to the west is an uplifted region of mainly metamorphic and granitic rocks, which lies between the accreted terranes of the Intermontane Belt to the west and the original North America to the east. The Intermontane Belt is generally of lower elevation, and comprises an amalgam of accreted terranes. It includes the Okanagan Valley and its smaller basins, and volcanic features of Tertiary age. In central and northern areas of the Intermontane Belt, amalgamation has generated uplift and sedimentation, including the Bowser and Sustut Basins. The Coast Belt, composed mainly of granitic and metamorphic rocks of the Coast Plutonic Complex, is rugged and has high relief. The Coast Belt is believed to have been created by a combination of subduction and accretion of the Insular Belt to the west. The Insular Belt includes the continental margin of Vancouver Island, the Queen Charlotte Islands (Haida Gwaii), southern Alaska, and the Saint Elias Mountains.

3.2.1 Volcanic Belts

Volcanism in the Canadian Cordillera has occurred from the beginning of continental accretion to recent times. Some volcanism occurred as a part of the process of continental accretion, some has been superimposed later as a result of plate subduction, some may result from hotspot activity (Bevier et al., 1979), and some likely results from deep faulting and extensional tectonics (e.g. Hickson, 1987). As a result, some Tertiary volcanic belts lie within the morphological belts described above, while others cut across belts. Figure 3.2 shows the volcanic centres of the Canadian Cordillera. Only Holocene, Pleistocene, and Pliocene volcanic centres are likely still hot enough to hold geothermal resources. Souther (1977) reviewed the history of volcanism in the Canadian Cordillera from Upper Paleozoic time to the present. Recent reviews focused on the Quaternary volcanism and include those of Hickson (2000), Hickson and Edwards (2001), and Stasiuk et al. (2003). Intrusive rocks, plutons, and batholiths are found in all morphological belts. Most are too old to have any residual heat, but many younger intrusives have significant heat generation from radioactive isotopes. Potassium-argon dates from some of the plutons range from 18 to 7.8 million years before present.

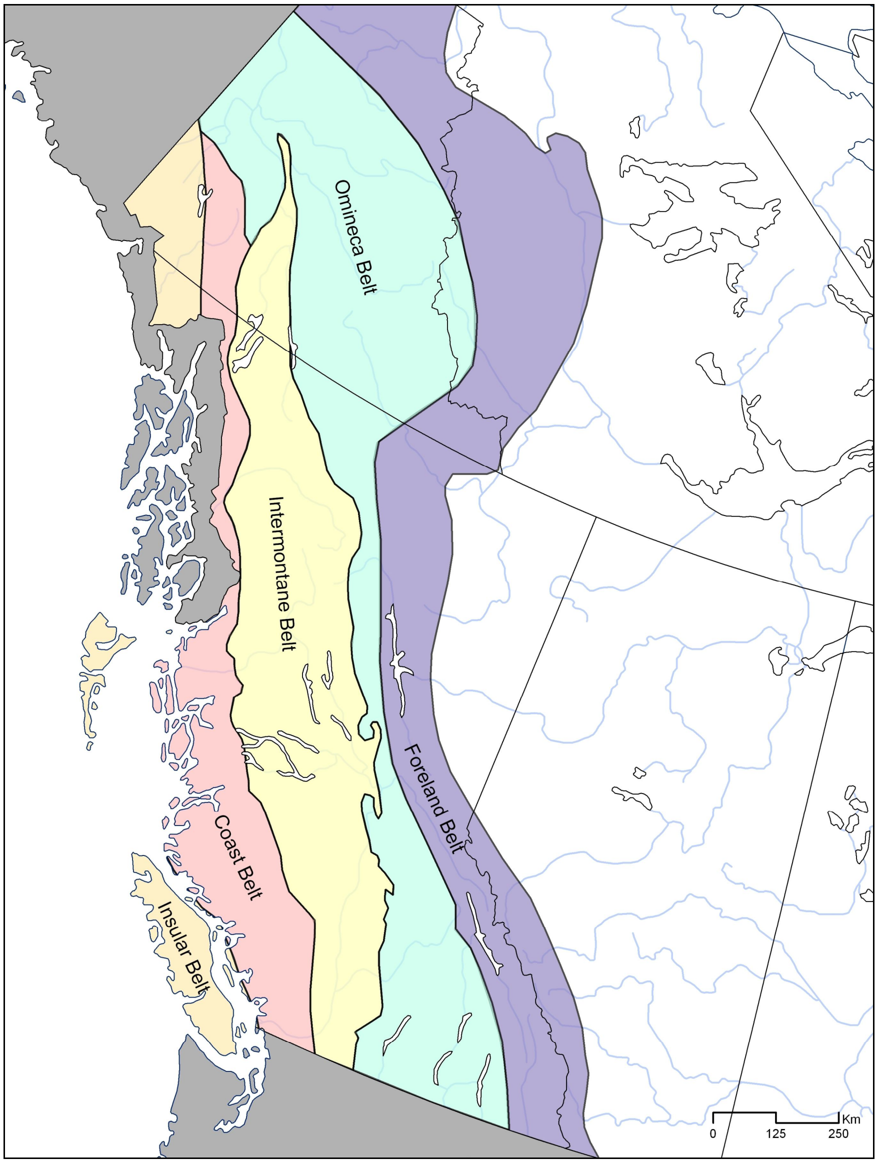


Figure 3.1. Morphological belts and strike slip faults of the Cordillera. Source: Lane (2005).

The Garibaldi Volcanic Belt runs roughly north to south and is related to subduction of the Juan de Fuca plate beneath North America (Bevier et al., 1979; Green et al., 1988; Rohr et al., 1996); it crosses the related Pemberton Volcanic belt at approximately 45 degrees. (The Pemberton Volcanic Belt runs south-east to northwest, parallel to the coast. It is of Neogene age and is related to an early stage of spreading from the Juan de Fuca - Explorer Plate system [Berman, 1981; Souther and Yorath, 1991]). The Garibaldi and Pemberton Volcanic belts contain more than 60 volcanic features of Pleistocene or younger age, including flows, domes, cones, spines, and various landforms produced by volcano-ice interaction, most of them clustered around the stratovolcanoes of (from south to north) Mount Garibaldi, Mount Cayley, Mount Meager, and Silverthrone caldera. More than a dozen Holocene eruptions are suspected based on outcrop characteristics (e.g. lack of evidence for glacial overriding, preservation of rapidly erodible textural features, etc.), but most of these young-looking rocks have not been radiometrically dated. The youngest explosive activity in Canada was an eruption of dacite pumice from Mount Meager, which produced the Bridge River Ash, identified over a wide area of southern British Columbia and as far as the Alberta border; it has been dated at 2350 years before present (Clague et al., 1995; Leonard, 1995).

The Anahim Volcanic Belt runs east-west between latitudes 52 and 53° N, from the west coast to the Interior Plateau near Quesnel. It includes at least 40 known or suspected Quaternary volcanic centres (mostly pyroclastic cones and thin lava flows) and a large number of earlier centres (cones, flows, and three Tertiary shield volcanoes which are probably extinct). The volcanoes generally become younger from the coast to the interior, with the most recent dated activity at Nazko cone at the east end, about 7,200 years ago (Souther et al., 1987). The Anahim Volcanic Belt is most commonly interpreted to have formed as a result of the North American continent sliding westward over a small "hotspot" or convective plume in the Earth's mantle, like that which feeds the Hawaiian Islands (Bevier et al., 1979; Souther and Clague, 1987). However, the small volcanoes of the Milbanke Sound group, at the extreme western end of the Anahim Belt, may have erupted after the last major glaciation, meaning they are less than 10,000 years old - much younger than would be expected by the hotspot theory. For geographical convenience, they are often grouped with the Anahim Volcanic Belt, but their tectonic affinity is poorly understood.

A zone of relatively small volume, flat-lying basaltic lava flows occurs inland of the Garibaldi Volcanic Belt and stretches across a significant area of the Interior Plateau of south-central British Columbia: these lava flows are known as the Chilcotin basalts, and their eruption may be related to back-arc extensional volcanism (Bevier, 1983; Mathews, 1989; Souther, 1991). Most of the Chilcotin eruptions took place 6 to 10 million years ago (Miocene), though a few occurred during the early stages of Garibaldi Volcanic Belt activity, 2-3 million years ago (Pliocene), and a few occurred during the Pleistocene (Mathews, 1989).

The Clearwater-Quesnel volcanic province of east-central British Columbia consists of a poorly-defined belt of volcanoes that extends northwest from Wells Gray Park to Quesnel Lake (Hickson and Souther, 1984; Hickson, 1987) and has been intermittently active over the past three million years. It includes numerous small volume basaltic volcanoes, many of which show evidence for eruption in contact with ice, with the youngest features postglacial. Volcanism in the region likely results from deep faulting and extension (Hickson, 1987).

In northern British Columbia (and parts of the adjacent Yukon and Alaska), the Northern Cordilleran Volcanic Province (NCVP, portions of which are known as the Stikine Volcanic Belt) runs roughly north-south and is one of the largest volcanic provinces in western North America. The volcanism is proposed to result from extensional forces acting on the northern Cordilleran lithosphere (Edwards and Russell, 1999, 2000). The NCVP is dominated by mafic alkaline volcanic rocks and contains more than 50 post-glacial eruptive centres and a similar number of late Miocene to Pliocene age. The belt includes some very large volcanic piles, such as the Edziza complex, which shows an eruptive record from Pliocene to recent time, and lava flows from the most recent eruption in Canada, which took place about 150 years ago in the Lava Fork area (Hauksdottir et al., 1994). The lava flows and cinder cones from the only historic eruption in Canada, that of the Aiyansh-Tseax River volcano, are clearly visible in the Nisga'a Memorial Lava Beds Provincial Park, about 60 km north of Terrace (Brown, 1969).

The Wrangell Volcanic Belt lies largely in Alaska, but also extends across the border into the southwestern Yukon, and is associated with subduction of the Pacific plate beneath the North American plate at the eastern end of the Aleutian Arc (Miller and Richter, 1991; Skulski et al., 1991). The Wrangell Volcanic Belt includes several large volcanoes that have been active in the Holocene, including the historically active Mount Wrangell, and also Mount Churchill-Bona, which has been proposed as the source for the two large Holocene White River ash deposits, the larger of which spread ash across most of the Yukon and the Northwest Territories.

3.2.2 Non-Volcanic Cordillera

Outside of major volcanic belts the Cordillera is characterised largely by deformed metasedimentary rocks. Regional studies of heat flow (Chapter 5) show large variability within the region, not always clearly attributable to geological features. There are, however, distinct regions that show great potential for geothermal resources. Thermal spring systems are abundant and indicate the potential presence of local geothermal anomalies. As well, earlier work has shown the presence of relatively young Tertiary igneous intrusions that still have high heat generation (Lewis et al. 1984). These specific regions are discussed below.

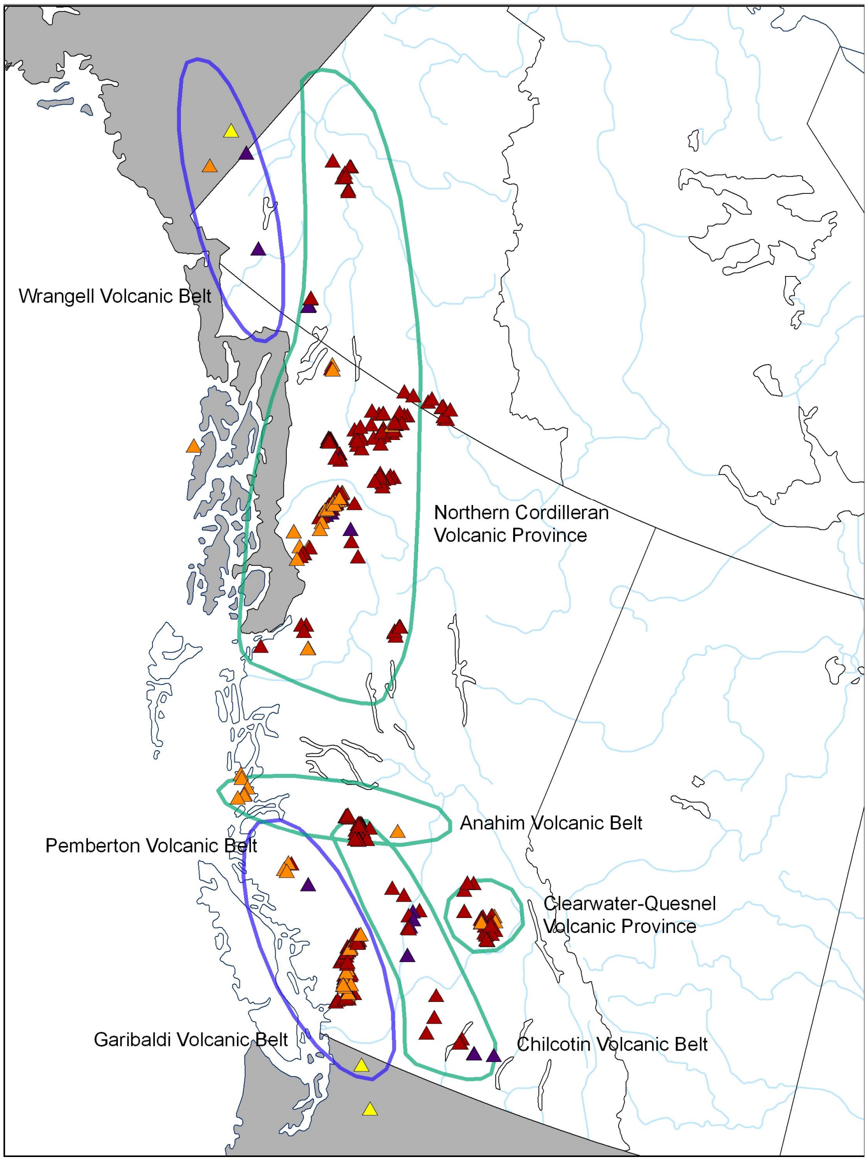


Figure 3.2. Location and age of volcanoes found in the Cordillera. Volcanic belts are shown with green (basaltic type) and blue (stratovolcano type) outlines.

3.2.2a Thermal Springs

Thermal springs are seen as a key exploration tool for defining areas with geothermal potential. The occurrence of a thermal spring shows an area has an active deep groundwater circulation system that may or may not indicate a local thermal anomaly. Geochemical techniques can also be used to better understand temperature gradients in the spring system, providing additional information on local thermal anomalies. In addition to their value as an exploration tool, thermal springs can also provide a means for direct use of geothermal energy by capturing the flow for variesous uses from spas to direct heating. Currently Canada has 12 developed thermal spring pools.

The definition of what constitutes a thermal spring varies, but typically the lower temperature limit of 'thermal' water is spring discharge that is greater than 10 °C above average air temperature (White, 1957). This definition is difficult to apply across Canada given the low average temperature of northern regions. Instead we use here a definition of thermal spring as discharge greater than 10 °C. This lower cut off opens the possibility for many small springs to be classified as thermal, and it is likely that numerous discharge sites at this lower temperature have not been recorded. Higher temperature springs (>20 °C) are more likely to be associated with steam formation in the winter, and associated algal and tufa deposits make them more readily identifiable. Based on this definition, over 140 thermal springs are known in Canada. These are entirely restricted to the Canadian Cordillera as shown in Figure 3.3 (Grasby and Hutcheon 2001, Grasby et al. 2000, Grasby unpublished data).

Stable isotope studies show that all thermal springs sampled plot along what is known as the global meteoric water line (Fig. 3.4). This line represents an empirical relationship between the oxygen and hydrogen isotope composition of water molecules defined by precipitation around the globe (Rozanski et al. 1993). The observation that thermal spring waters plot on this line indicates that they all originate as meteoric water. All thermal spring waters then start as rain or snow melt that circulate deep into the ground where it is heated, before returning to the surface. Thus along with a water source, a high permeability conduit that allows deep water circulation to occur is required. This explains the typical association of thermal springs with fault systems. A conceptual model for a flow system of one of the hottest thermal spring systems in Canada, Lakelse Spring, is shown in Figure 3.5.

Most thermal springs are associated with regions of high heat flow, such as the volcanic belts in the Cordillera; however, this is by no means a prerequisite. The depth of circulation, in relation to the local geothermal gradient, along with the rate of fluid flow, will dictate the final outlet temperature of the spring system. As such, the occurrence of a thermal spring does not necessarily indicate the presence of a thermal anomaly. For example, the thermal springs at Banff occur in one of the lowest heat flow regions of the Cordillera. However, in this location anomalous structural features associated with Cascade Mountain locally enhance permeability along the Sulphur Mountain thrust, allowing deep circulation of groundwater (Grasby et al., 2003). In this example, it is the enhanced depth of circulation that allows development of a thermal spring, rather than a local thermal anomaly.

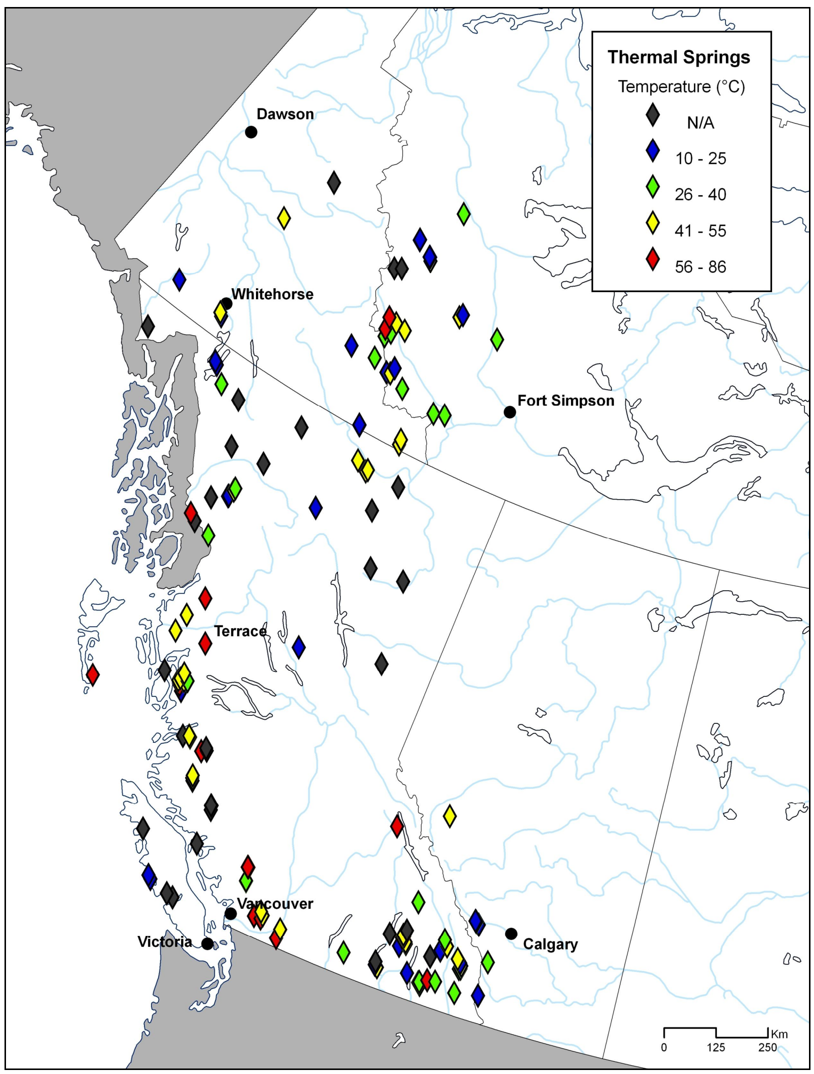


Figure. 3.3. Distribution of thermal springs in Western Canada with their relative temperatures. Source: Grasby et al. (2009).

The temperature of a thermal spring outlet reflects a combination of local geothermal gradient, circulation depth, and flow rate. The variability in heat flow and geothermal gradients in the southern Rocky Mountain Trench that affect thermal springs has also been shown by Allen et al. (2006), where a lower geothermal gradient requires a greater circulation depth for groundwater to obtain heat.

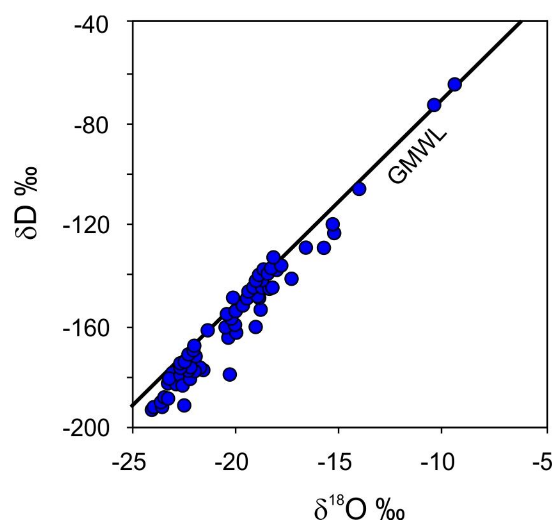


Figure 3.4. Plot of stable isotope values of thermal spring waters in Canada (blue dots). The observation that all thermal spring waters plot along the Global Meteoric Water Line (GMWL) indicates that thermal spring waters originate as precipitation, which then must circulate deep underground to be heated before returning to surface (see Fig. 3.5).

The depth of groundwater circulation is typically restricted by the strength of the rock that the groundwater flows through; increased stress at depth closes fracture networks, thereby inhibiting circulation. Empirical evidence suggests a practical limit for circulation is around 5 km (Ingebritsen and Manning, 1999), which is consistent with the deepest estimated circulation depths for springs in the Cordillera (Grasby and Hutcheon, 2001). Research has shown that if groundwater circulates too quickly, then advective heat transport will cool the region, while if it circulates too slowly, the groundwater will cool during its ascent to surface (Forster and Smith, 1988a, 1988b; Fergusson et al., 2009). Conversely, if there is too much groundwater flow then isotherms will be depressed by groundwater recharge and this will lower discharge temperatures. Ingebritsen et al. (1996) estimate that some cold springs with high discharge rates in the Cascades could be discharging the bulk of crustal heat flow over very large areas. These factors indicate that there is an optimal groundwater flow rate for thermal spring creation

(Forster and Smith, 1988a, 1988b; Ferguson et al., 2009). The perturbation of conductive geothermal gradients along with mixing of waters from different depths along faults that control the distribution of most thermal springs in Canada complicate the estimation of circulation depth. This has been attempted for selected thermal springs in British Columbia using chemical geothermometry and geothermal gradients from nearby boreholes (Grasby and Hutcheon, 2001; Allen et al., 2006) and circulation depths of 0.6 to 4.8 km were reported. Work by Ferguson et al. (2009) suggests that these estimates are subject to some uncertainty and likely underestimate circulation depth due to the input of water at various points along the fault. Actual circulation depths are likely to be 30% greater for many of these systems due to advection.

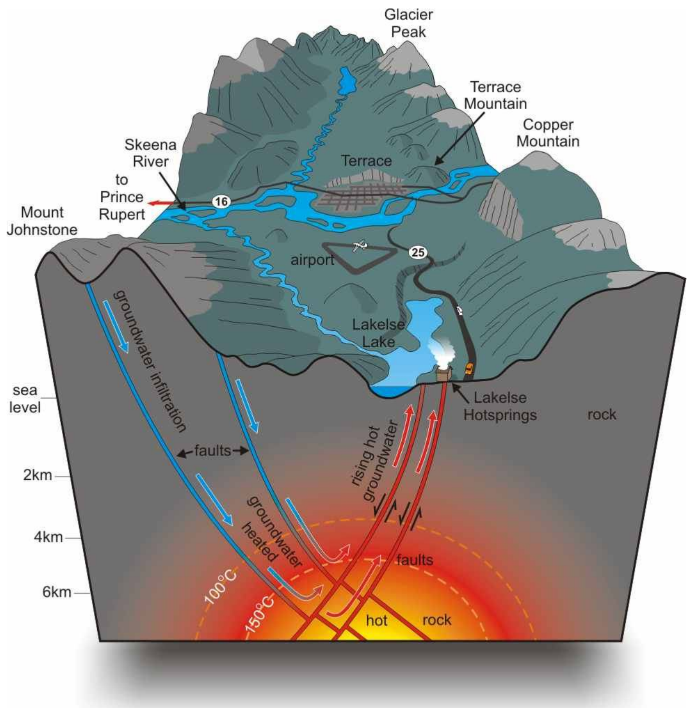


Figure 3.5. Diagram showing schematic model for the Lakelse Spring, NE British Columbia. Source: B. Turner, Geological Survey of Canada).

Unique and rare ecosystems are commonly associated with thermal spring outlets (Fig. 3.6). The northern limit of most plant and animal species is often a function of climatic factors (e.g. how cold a winter they can survive). In Canada’s North, the discharge of thermal waters creates warm microclimates, often without snow, and with green plants persisting through the cold winter months. These warm microclimates allow plant species to survive as isolated communities at climates much farther north than their normal distribution. As an example, the southern Maiden Hair Fern is an endangered plant in Canada found only at the Fairmont Hot Spring. This location is ~1500 km north of the next known occurrence. There are also several other known northernmost occurrences of animal species at thermal springs (e.g. the Vivid Dancer Dragon Fly). In addition, there is one documented case of an endemic species that has evolved exclusively to live within the thermal waters of a spring system. The Banff Springs Snail likely evolved from cold water cousins within the last 5,000 years into a new species that can only survive in the Banff Springs thermal waters (Grasby and Lepitzki, 2002).

Figure 3.6. Photos of endangered species found at some thermal springs in Canada; the Maiden Hair Fern (left), Vivid Dancer Dragonfly (centre) and Banff Springs Snail (right).

Figure 3.7. Travertine mound forming at the Sculpin warm spring, Mckenzie Mountains, NWT.

Along with hosting rare ecosystems, spring outlets often develop extensive travertine mounds as unique hydrogeological features. These mounds are typically formed by calcium carbonate precipitating from solution in response to degassing of carbon dioxide (CO_2) as the waters equilibrate to atmospheric pressure. This degassing can result in the formation of extensive structures that grow and spread over thousands of years. Numerous spectacular examples occur throughout Canada (Fig. 3.7). Given these rare ecological and hydrogeological features, including several known endangered species, protection of thermal springs sites should be an integral part of any geothermal development. Any production should be guaranteed not to interfere with the natural operation of these systems.

3.2.2b Tertiary Intrusives

In the Canadian Cordillera, many surface exposures of intrusive rocks have been sampled and heat generation has been measured. Lewis et al (1984) and Lewis and Bentkowski (1988) published compilations of heat generation data. The distribution of observed heat generation is shown in Figure 3.8 and a list of granitic plutons and their heat generation is given in Table 3.1 (Lewis et al, 1992). These data indicate several plutons that should be examined for hot dry rock potential, particularly younger Tertiary intrusives with high content of radiogenic elements. The distribution of Tertiary instrusives is provided in Figure 3.9. While most have no associated heat generation data, they are of similar geological age and rock type, suggesting that they also have similar potential. More fundamental data gathering is required to further characterise these relationships. Limited studies conducted as part of the previous National Geothermal Program did show, however, that Tertiary intrusives can have significant heat generation and high geothermal gradients associated with them (see section 4.2.2).

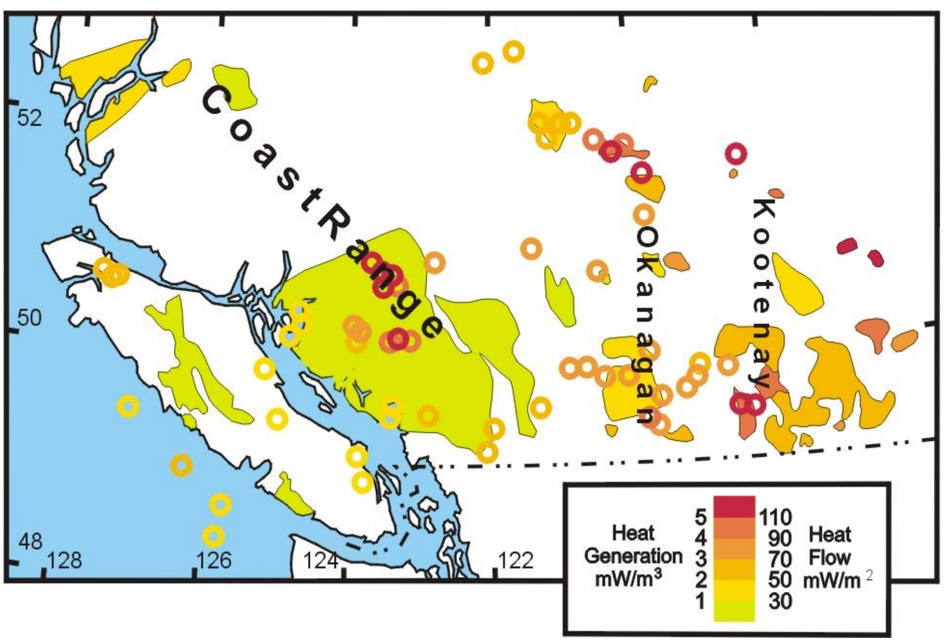


Figure 3.8. Distribution of measured heat generation in intrusive bodies in the southern Cordillera. Heat generation is shown by coloured patches and heat flow is shown by coloured circles. Source: Lewis et al. (1992).

Table 3.1 Heat generation in granitic plutons (n= number of samples, A= heat generation and SD= standard deviation)

Name	n	A ($\mu W/m^3$)	SD
Insular Belt			
Island intrusions	65	0.78	0.25
Coast Plutonic Belt			
Chillwack	9	1.7	1.48
Coast Plutonic complex	87	0.82	0.61
Mt. Barr	5	2.05	0.38
Needle Peak	1	1.49	-----
Intermontane Belt			
Guichon	6	0.83	0.27
Pennask	3	1.75	0.43
Similkameen	12	1.31	0.22
Takomkane	32	0.95	0.27
Omineca Crystalline Belt			
Baldy	3	4.84	1.12
Battle Range	5	4.67	0.86
Bayonne	8	2.28	0.7
Bugaboos	18	6.15	1.33
Coryell	34	4.78	1.35
Crawford Bay	7	2.69	0.29
Fry Creek	18	4.85	1.17
Galena Bay	6	1.69	0.21
Horsethief	14	6.51	1.85
Kuskanax	4	1.15	0.11
Lost Creek	5	3.55	0.35
Nelson	32	2.12	0.98
Raft River	41	4.35	1.39
Salmon Arm	5	3.37	0.44
Shepphard	7	1.75	0.27

Source: Jessop, 2008

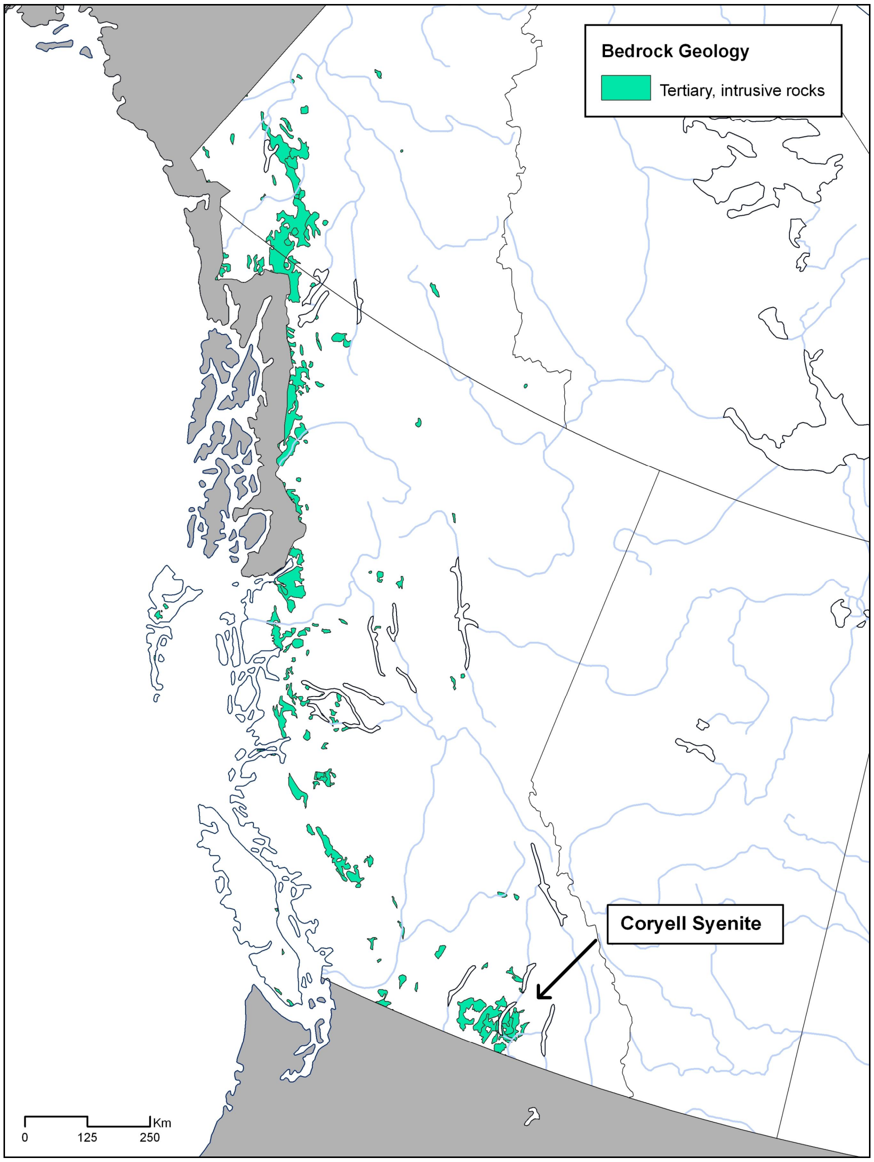


Figure 3.9. Tertiary intrusive rocks of western Canada.

3.3 SEDIMENTARY BASINS

Canada is covered by sedimentary basins that contain a significant amount of fluid in porous rocks (Fig. 3.10). Most of this fluid is water, but oil and gas occur in locations where these lighter fluids may be trapped. The temperature of water depends on the local geothermal gradient, which, because of the relatively low thermal conductivity of sedimentary rock, may be from 25 to 40 °C/km. The highest temperatures found in these sedimentary rocks are also a function of thickness of the sedimentary basin. While basins with extensive exploration history have detailed knowledge of sediment thickness, other basins have very limited information. Overall, geothermal resources of sedimentary basins in Canada are typically moderate to low temperature. Locally, temperatures that exceed 150 °C are measured at depths as shallow as 3 km. While the high range of temperatures give potential for direct electrical generation, successful application of binary systems has allowed electrical generation from produced formation waters in other countries down to 80 °C, as well as direct use applications.

Canada has numerous sedimentary basins across the country (Fig. 3.10). There is significant variation in the degree of knowledge of these basins, from very basic information of their surficial distribution to some of the best characterised 3-D models of sedimentary basins in the world. By far the largest and best characterised sedimentary basin is the Western Canada Sedimentary Basin (WCSB), which extends from the foothills of Alberta and northeast British Columbia, eastward through southern Saskatchewan and into southwestern Manitoba, as well as north into southwestern Northwest Territories. The basin, with a maximum depth of nearly 5.4 km (Hitchon, 1984; Sproule and Angus, 1981), has been the focus of extensive petroleum, coal, and potash development in Canada. Publically available data produced by the petroleum industry provides a significant resource to increase our knowledge of the geothermal potential in the WCSB and regional studies have already defined areas of anomalous high temperatures (Fig. 3.11). Other significant basins in Canada that have been assessed to some degree for geothermal potential include the Cumberland Basin in Atlantic Canada, part of a group of Carboniferous basins in the area, which contains up to 9 km of sediment. Other smaller Carboniferous sedimentary basins in Nova Scotia and New Brunswick, the Quebec Basin, the Michigan Basin, the Mackenzie Delta – Beaufort Sea Basin, and the Sverdrup Basin in the Arctic Islands were also investigated. Jessop (1976) provided the first preliminary overview of the geothermal potential for these basins.

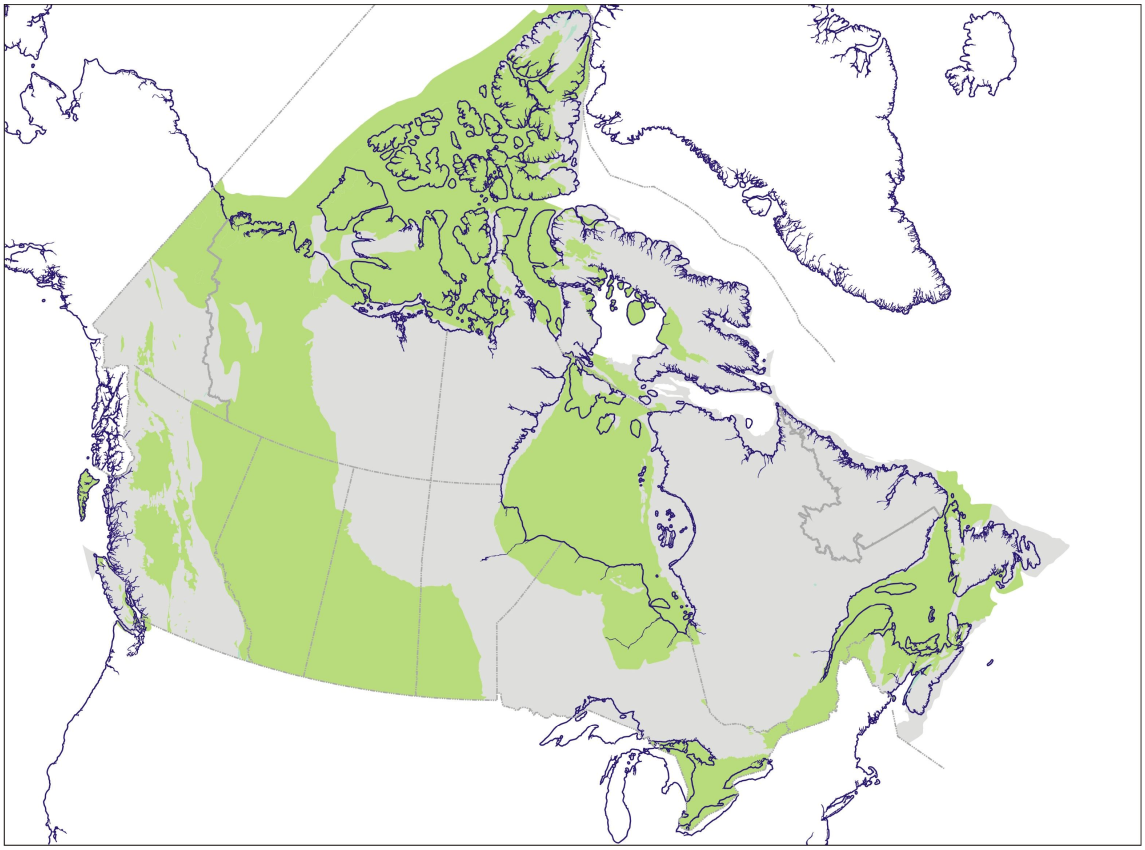


Figure 3.10. Map showing regions of Canada covered by Sedimentary basins (green areas).

Temperature in sedimentary basins is surprisingly difficult to determine. Although well logging provides a large number of data, they are of variably quality. Temperatures can be derived from a variety of sources, including: 1) Bottom-hole temperatures (BHTs) from geophysical log-headings that are usually recorded by maximum-reading thermometers, which are intended to reach their maximum temperature while near the bottom of the well before the upward logging run. Bottom-hole temperatures are taken at the time of maximum disturbance of the well. 2) Drill Stem Test (DST) temperatures recorded when a segment of the well is packed off and fluids are produced from adjacent formations at specific depths. 3) Production Tests, where temperatures are measured from producing wells that are more likely to be in thermal equilibrium as they have been producing fluids for an extended period of time, and 4) Down-hole temperature logging, usually done during research studies and focused on data collection at some point after drilling operations have ceased. All of these data sources are subject to significant and unpredictable instrumental and human error. Despite their inaccuracies, large numbers of existing temperature measurements (likely in the millions) may, by statistical treatment, give a general picture of temperature distribution and the major regional anomalies. A significant challenge remains to compile digital data records, as most temperature measurements from sedimentary basins are only available as paper or microfiche records.

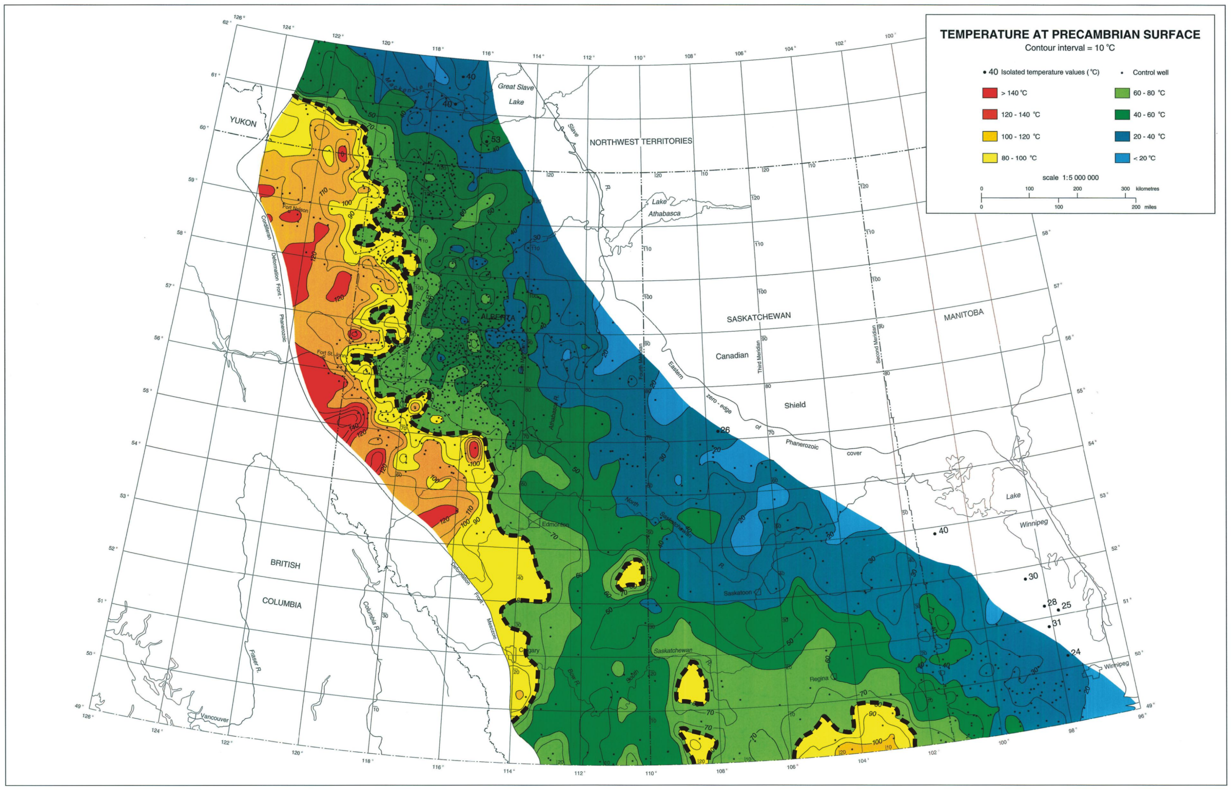


Figure 3.11. Temperature at the base of the sedimentary column in the Western Canada Sedimentary Basin. Source: Bachu and Burwash (1994). The dashed lines divide areas with bottom-hole temperatures above (warm colours) and below (cool colours) 80 °C.

3.3.1 Co-Produced Fluids

Co-produced fluids are a geothermal resource which may be exploited in combination with oil and gas development. In exploitation of oil and gas production wells, hydrocarbons must be separated from co-produced water before being refined. The hot water/brine once separated is considered waste and is typically disposed of, which is often costly to the supplier. By installing a binary cycle into the well system, the hot water/brine may instead be used to generate electricity before being reinjected back into the well, providing both economical and environmental benefits to the supplier. Considered a relatively straightforward process, the integration of binary technologies with existing infrastructure eliminates the need for expensive drilling, hydrofracturing operations, and costs associated with the disposal of waste water (GEOFAR, 2009). Power produced from co-produced fluids may be used within the operating system, reducing the energy demands of the well while substituting fossil fuel generated power with renewable power.

Oil fields in the US with adequate flow rates and geothermal fluids ranging from 120 °C to over 200 °C are said to provide a geothermal potential in the thousands of MW (GEOFAR, 2009), with the greatest potential in Texas, Oklahoma and California. Two demonstration projects are already underway in the US. The Jay Oil Field in Florida has the potential to produce 1 MW of power, or about 5% of the field's total electricity demands, while Rocky Mountain Oil Test Center in Wyoming generates more than 250 kW of power from geothermal fluids measuring 87 °C (GEOFAR, 2009).

Co-produced geothermal power in Canada is growing in interest. At the close of 2009, the Alberta Energy Research Institute (AERI) approved a $2.6 million grant to Free Energy International and Borealis GeoPower for a project which aims to produce geothermal power from hot water within mature oil wells in Swan Hills, Alberta. If successful, this project may support growth for geothermal power production in oil fields across other regions of Canada where temperatures and flow rates support such technology.

3.4 CANADIAN SHIELD

The Canadian Shield represents a large geographic region characterised by igneous (granitic) and metamorphic (gneissic) rocks, which extends from the Arctic Archipelago, south to eastern and central Canada. The region is composed of some of the oldest crustal rocks on Earth (3.96 billion years), the majority of which are greater than 2.5 billion years old. The Shield represents an amalgamation of early Earth continental blocks along with suture zones formed during continental collision and amalgamation. The region originally would have been characterized by large mountain ranges and volcanic complexes; these, however, have been eroded away through time leaving only the 'roots' of the mountains exposed. Given the great age of these rocks radiogenic elements have all undergone significant radioactive decay, such that current heat generation in the Canadian Shield is very low. As well, the thermal conductivity of granitic and gneissic rocks, which dominant the Canadian Shield, is significantly higher than sedimentary rocks, meaning the any heat generated is readily conducted to the surface, lowering geothermal gradients. Although for large portions of the Shield no data exists, in general the Shield region has some of the lowest geothermal gradients in Canada. As well, the granitic and gneissic rocks have no inherent permeability, although large fracture systems do store and conduct water. In general, there is to be no expectation of underground reservoirs of thermal waters, such that even if localized heat resources do exist, these prospects could only be produced through Enhanced Geothermal Systems (Chapter 8).

While the low heat flow of the Canadian Shield, typically less than 60 mW/m^2 (Figure 5.2), makes geothermal resources less attractive, some settings are favourable to the operation of ground source heat pump systems. The thermal conductivity of the igneous and metamorphic rocks of the Canadian Shield can be above 3 W/mK (Figure 5.5b). This high thermal conductivity for rock allows efficient heat transfer by conduction, providing an advantageous medium to install ground-source heat pumps. Heat exchangers made of a closed-pipe loop installed in a borehole can be short when the subsurface thermal conductivity is high, which reduces the installation cost of the system.

Low-temperature geothermal resources associated with flooded underground and open pit mines, which can be exploited with groundwater and surface water heat pumps, are also significant in the Canadian Shield. The exploitation of major mineral deposits in Ontario near Sudbury and Timmins, and in Québec near Rouyn-Noranda and Val D'or, left behind abandoned mines that now form water reservoirs attractive for heat pumps systems. The mines were mostly exploited for base metals and can be deep and large. For example, 5.37×10^7 tons of ore were extracted up to a depth of 2440 m at the Horn Mine under Rouyn-Noranda (Chapter 6). Water flooding that mine is estimated to contain 104 TJ of geothermal energy, assuming that the water temperature can be decreased by 5 K using heat pumps. The Horn Mine sits directly under urban areas of Rouyn-Noranda - potential users of heat pump systems. This example is one of the hundred plus mines in the Canadian Shield that contain low-temperature geothermal resources, which can be exploited at a district scale. Currently, the City of Yellowknife is planning to develop such a heat pump system from the nearby abandoned Con Mine.

4. PREVIOUS CANADIAN GEOTHERMAL ENERGY RESEARCH

4.1 INTRODUCTION

This chapter reviews the scope of activities of the National Geothermal Energy Program, which operated from 1974 until 1986, under Natural Resources Canada predecessor department, Energy, Mines and Resources Canada. The goal of this chapter is to provide information on the nature of research and pilot programs conducted and the outcomes achieved prior to the Program's end.

Scientific programs related to geothermal systems had been operating for many years in Canada. Early heat flow measurements were made by groups at the Universities of Toronto and Western Ontario. A geothermal research group had been established in 1962 at the Dominion Observatory in Ottawa, later renamed Earth Physics Branch (EPB). Within that group, heat flow and heat generation were measured in many areas of Canada, and, by 1976 the thermal regime of the crust was known in a broad regional manner, and equipment was available for detailed surveys of specific localities. Volcanology had long been a part of the activities of the Geological Survey of Canada (GSC), mainly in the Vancouver office. Volcanic centres of the major volcanic belts and known hot springs within the Canadian Cordillera had been mapped and locations of known hot springs had been mapped over many years. Scientific staff of EPB and GSC had worked together on projects of scientific geothermics since 1965, and they began to cooperate on projects related to geothermal resources in early 1974. In the winter of 1974 the GSC and EPB, both branches within the Department of Energy, Mines and Resources (EMR) began a small-scale investigation into the potential for geothermal energy in Canada. In 1976 the Department of Energy Mines and Resources initiated The Geothermal Energy Program. This program ran from April 1st 1976 to March 31st 1986, with a total budget of $6 million (in 1980's dollars). This sum does not include any spending under Federal-Provincial Agreements on Energy (CREDA) or any spending from scientific budgets before, during or after the formal Geothermal Energy Program. The key elements of this

Program are summarised here. Details of work conducted and major findings are provided in two reports summarising work on the Canadian Cordillera (Jessop, 2008a) and Sedimentary Basins in Canada (Jessop, 2008b).

Research into geothermal energy in Canada from 1974 to 1986 can be divided roughly into four phases, with no fixed time boundaries and considerable overlap. Phase one consisted of the examining the accumulated geological knowledge and was directed towards two main questions. Where are the Canadian resources? and how large are they? During the first phase, which lasted from about 1974 to 1977, objectives became focussed towards two demonstration projects and four geological regions.

The examination of these sites and regions constituted the second phase and addressed the questions: What is the geothermal potential for electrical generation at the Meager Creek, B.C. demonstration site? What is the geothermal potential at Regina demonstration site, and how can it be integrated into the energy supply of the University campus? What parts of the Tertiary and Holocene volcanic areas of Canada offer geothermal resources? What parts of the Cordillera, not of recent volcanic origin, offer geothermal resources, and of what type? What is the potential for low-temperature geothermal energy from Canadian sedimentary basins? What is the geothermal potential of the Atlantic Region, where costs of conventional energy are higher than the national average?

The question of shallow (<100 m) resources and the use of ground-source heat pumps was not raised and was not included in the mandate of the Geothermal Energy Program. Funding levels of the Geothermal Energy Program were inadequate to mount an EGS experiment. However, some basic Earth science research was conducted to provide information about possible sources.

Around 1980, the Program entered a third phase, in which the emphasis changed from the application of geoscience to the assessment of the resources and the application of engineering to assess the technology and economics of utilisation. The questions asked in this third phase were: What is the available technology to be learned from other countries, for development in Canada? What are the economic facts governing the use of geothermal energy in Canada? What are the institutional, legal, and fiscal factors governing the use of geothermal energy in Canada?

From about 1983, the fourth phase of the Program produced a series of requests for advice and assistance, mainly from municipalities concerned with the cost of energy supply for public buildings within their jurisdiction, or with novel ways of reducing costs. These purely local questions developed into studies of feasibility, drawing on the developed experience in geoscience, engineering and economics, each one directed at a specific location. By March 1986, the Geothermal Energy Program had established that there was a demand from the public for advice and assistance in the examination of geothermal resources, but at this point the Program was cancelled.

A bibliography of all publications resulting from this Program, in addition to others related to geothermal potential in Canada, is provided in Appendix 1. This bibliography is divided into two parts: those publications related to geothermal energy and those related to scientific geothermics.

4.2 MAJOR RESEARCH PROJECTS

4.2.1 Meager Mountain

The Meager Mountain volcanic complex is made up of several eruptive centres, including Mount Meager itself, Plinth Peak, Pylon Peak, Mount Job, and Mount Capricorn. It is one of a chain of volcanoes of Quaternary age that forms the Garibaldi Volcanic Belt, which runs roughly north-south to the north of Vancouver, B.C. Rocks from the Garibaldi group of volcanoes range from 4 My to less than 100 kY, which means that they are roughly of the same age as the Cascade volcanoes of the US. The older Pemberton Volcanic Belt, age 8 My to 18 My, runs roughly northwest to southeast, and the two belts meet close to Meager Mountain, as shown in Figure 4.1. The two volcanic belts are superimposed on the Coast Plutonic Complex, an older granitic and metamorphic terrain that extends northwestward from Vancouver the length of the Canadian Cordillera. The geology of the Meager Mountain Complex is shown in Figure 4.2.

Early work at Meager Mountain and in the Meager Creek valley has been described by Lewis and Souther (1978). The first contracted work aimed at evaluating the geothermal resource was the drilling of two short diamond drill holes at the hot springs of Meager Creek in March 1974. The first borehole was drilled in the snow-free area. The borehole first penetrated about 10 m of impervious gravel that was tightly cemented by deposits of travertine and opaline silica. Once the drill broke through into porous gravel, hot water at about 59 °C began to flow from the collar. The temperature profile showed that the hot water, moving downstream in the gravels, had cemented a cap within the gravels, and was escaping to form a major spring system where the cap was breached. The second borehole was drilled on the flank of the hot spring area. The entire borehole was drilled in quartz diorite gneiss. The temperature profile showed that warm water was entering the hole and was flowing to the surface in the new conduit. A third well was drilled by contractors for British Columbia Hydro (BC Hydro) about a kilometre upstream from the springs, near an area of warm seeps.

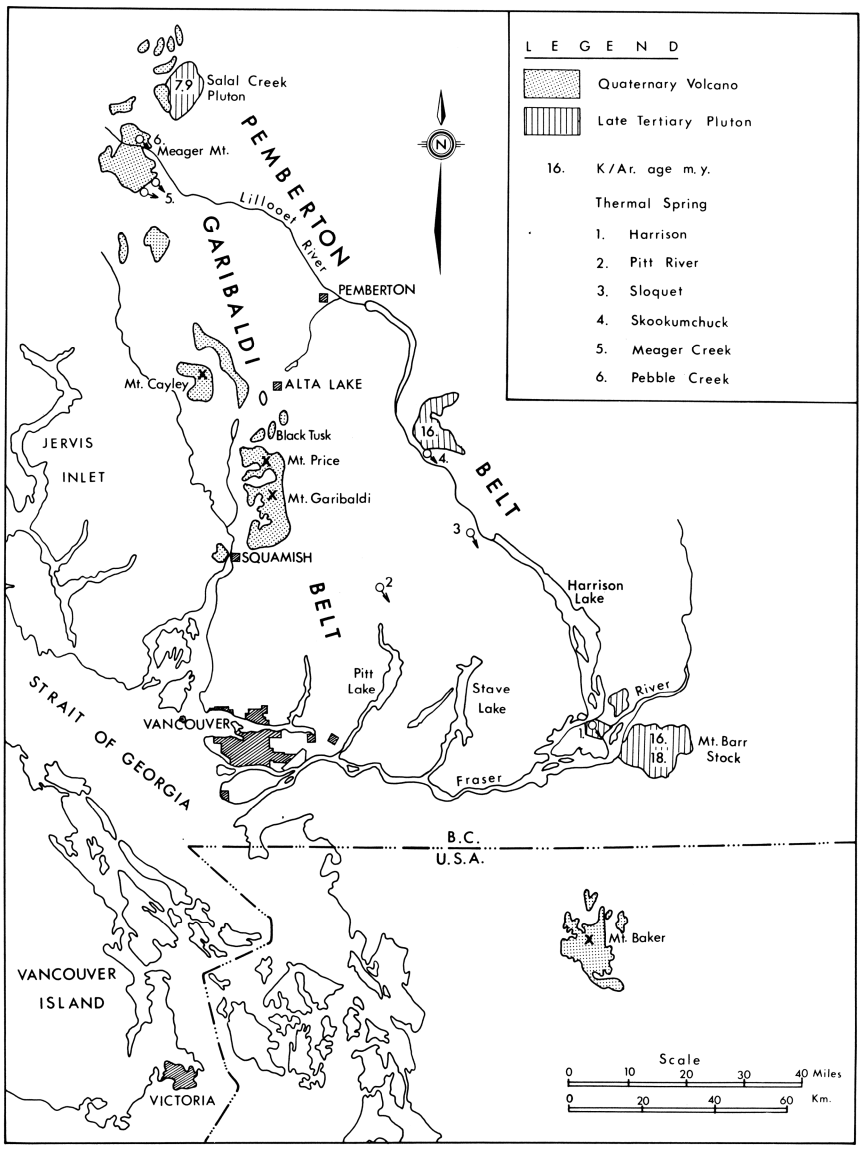


Figure 4.1. The location of Meager Mountain and other volcanoes of the Garibaldi Belt, in relation to towns and cities in southern British Columbia. Source: Lewis and Souther (1978).

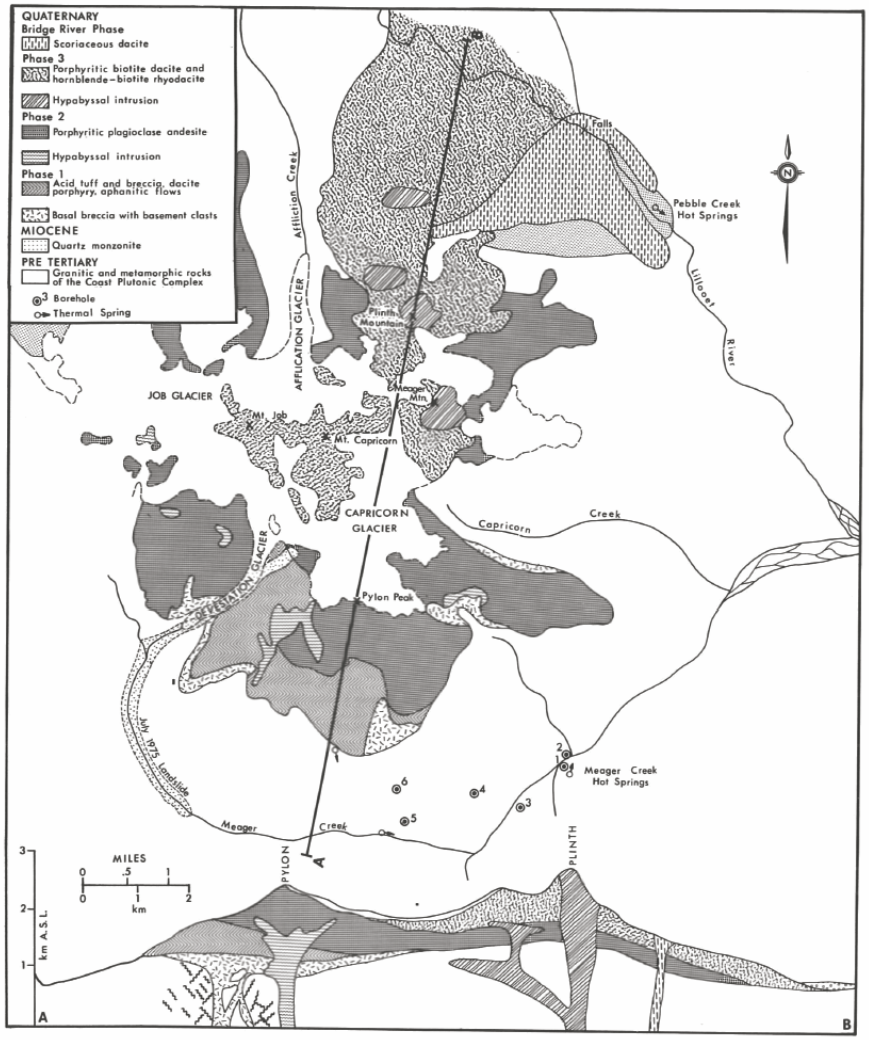


Figure 4.2. Geology of the Meager Mountain Volcanic Complex. Locations of some of the early diamond drill holes are shown near Meager Creek. Source: Lewis and Souther (1978).

Eventually, thirteen more diamond drill holes were drilled by Nevin Sadlier-Brown Goodbrand (NSBG) for BC Hydro further up the valley at sites within the area of a deep resistivity anomaly. One borehole (M7) showed a temperature of 200 °C at a depth of 365 m, a result that demonstrated the presence of strongly convective hydrothermal systems and strongly suggested a significant geothermal resource. Conductive temperature gradients, where it was possible to separate them from hydrological effects, were in the range of 112 to 289 mK/m, from four to ten times normal values.

From 1974 to 1978 EMR and BCH, through their contractors NSBG, worked in informal cooperation, with constant communication. EMR drilled the first holes at the hot springs, but after that concentrated on geological mapping, magnetotelluric surveys, trace-element soil and water surveys, and temperature logging in all available holes. BC Hydro concentrated on further shallow drilling and electrical resistivity surveys.

Lewis and Souther (1978) reported on temperature gradients and heat flow in the six existing boreholes. The last three, all drilled by NSBG for BC Hydro, showed temperature gradients of 112, 365 and 289 mK/m. Heat flows were 100 and 290 mW/m^2 for boreholes 4 and 5, but the last one had not penetrated rock where conduction was the only heat transfer mechanism.

As recounted above, the Meager Mountain Complex is one of three main volcanic centres of the Garibaldi Volcanic Belt. In addition to the detailed exploration of the Meager Creek Valley, regional studies were undertaken to provide an understanding of the whole volcanic belt. In the autumn of 1977, four diamond drill holes were drilled to depths of about 200 m for thermal studies. Sites were chosen for ease of access and proximity to Mounts Meager and Mount Cayley. Observed thermal gradients were all in excess of 45 mK/m and heat flows were all in excess of 69 mW/m^2. The highest heat flow, at a site 7.3 km east of amount Meager, was 132 mW/m^2, about double the world average (Lewis and Jessop, 1981).

In 1980 two boreholes were drilled above the valley on the west side of Mt Cayley, and in the following two years two more boreholes were drilled on the east side. Temperature profiles showed geothermal gradients of 90 and 95 mK/m, well above normal gradients, while the others showed values of 45 and 50 mK/m.

In 1983 NSBG published a report of heat flow calculations from all diamond drill holes in the Meager Mountain area. Temperature profiles in boreholes in the area of the resistivity anomaly on the south side of the mountain are shown in Figure 4.3.

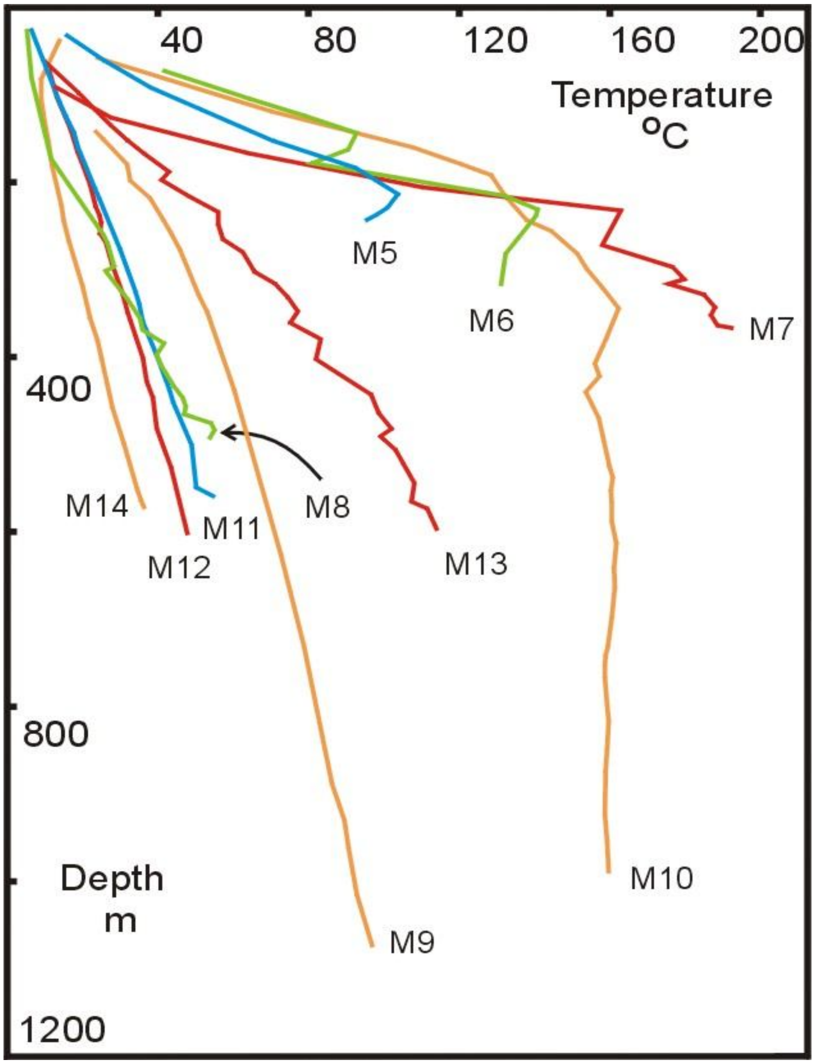


Figure 4.3. Temperatures from all diamond drill holes in the area of the resistivity anomaly on the south side of Meager Mountain. These temperatures were taken daily at the bottom of the hole at the end of each drilling day, to minimise distortion caused by water movement in the hole. Later temperature profiles may be quite different from these.

Based on the encouraging results from the shallow, slim-hole drilling program, three deep, full diameter wells (20 cm at bottom) were drilled during 1981-82. The drill collars were close to each other, near the site of the diamond drill holes M4 and M10. The first deep well, MC-1, was drilled to a length of 3,038 m and a depth of 2,500 m below the collar elevation, at an azimuth of 335°, approximately in the direction of Pylon Peak. Well MC-2 was drilled to a length of 3,500 m and a depth of 3,158 m at an azimuth of 30°. Well MC-3 was drilled to a length of 3,500 m and a depth of 3,024 m at an azimuth of 295°. Depths and directions were designed to test a substantial part of the known resistivity anomaly.

Well MC-1 flowed unassisted, and from November 1982 until the summer of 1984, steam was provided intermittently to a 20 kW demonstration plant provided to BC Hydro by the Electric Power Research Institute. This represents the first electrical generation by a geothermal source in Canada.

Well MC-2 intersected a major permeable zone between 1,600 and 1,800 m, which was interpreted as being associated with the Meager Creek Fault, and a further permeable zone at 2,600 to 3,000 m. Some of the fracture permeability may have been damaged by invasion of lost drill fluid. A maximum bottom-hole temperature of 270 °C was observed, but the well was not proved capable of sustained discharge.
Well MC-3 encountered substantial fluid loss at a length of 3,025 m, probably in the No-Good Fracture Zone. Tests indicated a maximum temperature of 290 °C, but this was not confirmed by reliable temperature logs. The well was not proved capable of sustained discharge. As in MC-2, permeability may have been damaged by drill fluid.

The high temperatures observed were quite adequate for a producing geothermal system. However, the water and steam flows indicated by testing were not sufficient for economic power production. Permeable zones were encountered in all three wells, but permeability was always in fracture zones or associated with dykes. Some permeable zones were damaged by being plugged with drill fluid or with material introduced to maintain drill-stem circulation.

BC Hydro (1983) published a summary report showing many details of the completion of the deep wells, their setting in relation to exploratory work, and the results obtained. Except for testing of the deep wells, geothermal exploration at Meager Mountain was suspended by BC Hydro in August 1982.

A resistivity anomaly was identified on the north side of the Meager Mountain complex. Because geophysical surveys were prevented by the high rugged terrain in between, it was not possible to confirm that this was a continuation of the south reservoir. Eight exploratory diamond drill holes were drilled in the area of the north reservoir between 1978 and 1983. Observed temperatures are shown in Figure 4.4. A further borehole was drilled about 4 km to the northwest, near Silt Lake. The temperature gradient at this site was observed to be about 55 mK/m.

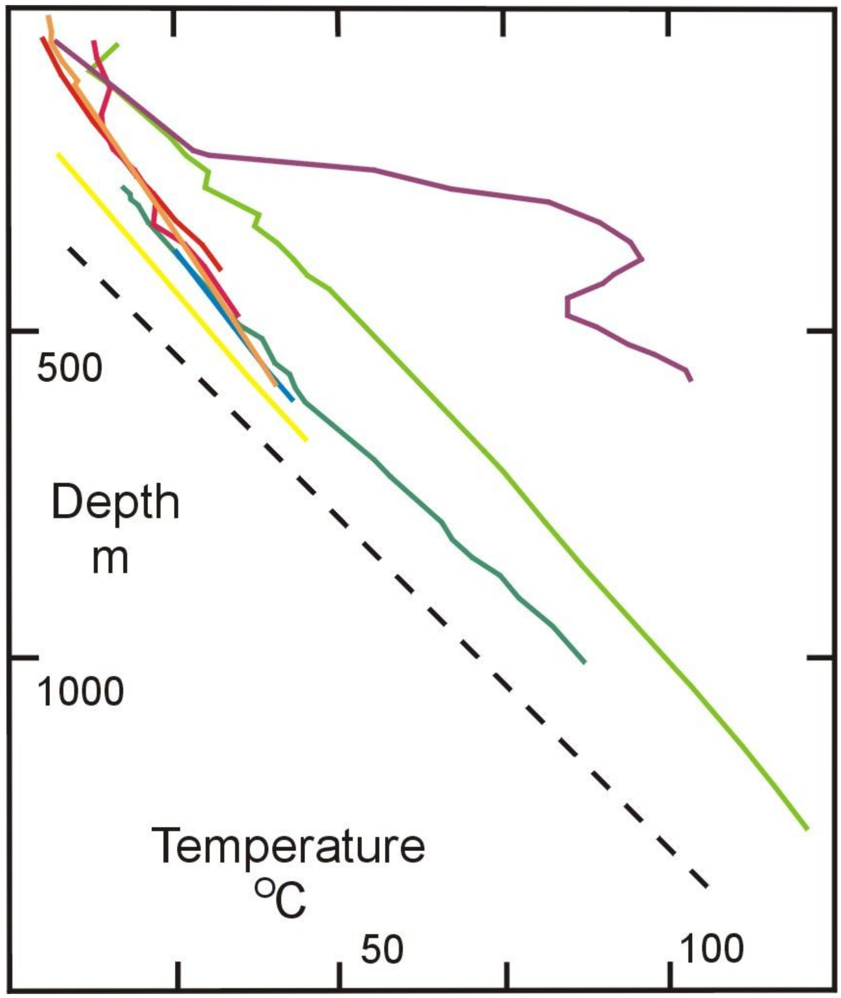


Figure 4.4. Temperature profiles from diamond drill holes on the north side of the Mount Meager Volcanic Complex. The dashed line shows a geothermal gradient of 100 mK/m. Diagram redrawn from BC Hydro (1983).

In 1984 the geothermal program of BC Hydro was cancelled and the managing team was dispersed. The large pool, built by BC Hydro at the hot springs was destroyed, but recreational users continued to go to the springs. Enough research and exploration had been completed at and around Meager Creek to show that there is a major geothermal anomaly associated with the volcanic complex. Although none of the three large wells was developed as a producer, many parts of the hydrothermal system remained untested, and it seems probable that there is a viable hot water, or even dry steam, resource present. A hot dry rock resource has been conclusively demonstrated and could be developed through EGS technology.

Andrew Nevin, previously of NSBG, has acquired the leases for the geothermal area on the north side of Meager Mountain. Ram Power Corp. now holds the leases for the southern side of Meager Mountain.

4.2.2 Other volcanic belts

The Anahim Volcanic Belt was originally defined as extending from the coast of British Columbia eastwards for about 500 km, at a latitude of 52 °N, with decreasing age eastward. Eleven shallow holes in the area of Hundred Mile House showed geothermal gradients in the range 21.5 to 30.5 mK/m. These gradients, combined with thermal conductivity estimated by rock type, will give heat values at about the world average. About 60 km to the south, in the Raft Batholith temperature gradients at four drilling sites were observed to be between 27 and 36 mK/m, and heat flow is in the range 92 to 114 mW/m^2. At the western end of the Anahim Volcanic Belt, two boreholes were drilled near Bella Bella, on Denny Island. These gave temperature gradients of 27.4 mK/m, and 32.2 mK/m, both calculated from bottom-hole measurements during the drilling process. Thus, it has not been observed that the Anahim Volcanic Belt shows consistent anomalous heat flow or temperature gradient, and it probably does not present geothermal energy potential greater than regions outside volcanic belts.

The volcanic structures of the Stikine Volcanic Belt are generally too far north and remote from human habitation or from electrical transmission lines to be of any interest. Except for detailed geological mapping (Souther, 1977) and a modest program of heat flow measurement (Jessop et al., 1984b), both undertaken before the Geothermal Energy Program, no geothermal exploration has been attempted.

4.2.3 Non-volcanic Cordillera

The conventional generation of electrical power from geothermal steam depends on the presence of a high-temperature heat source and a supply of water to carry the heat to the surface. In the parts of the Cordillera that are not of recent volcanic origin these heat sources are not present. However, there may be heat sources of acceptable temperature in Tertiary plutonic rocks, with or without water reservoirs.

Studies of both terrestrial heat flow and heat generation were the prime tools in this research. Heat flow measurement requires direct measurement of temperature and geothermal gradient, and so provides indications of where thermal gradients are above average. Measurement of heat generation of surface samples taken from batholith and intrusive bodies provides an indirect indication of heat flow, based on the assumption that the measured heat generation is representative of the rocks to a depth of about 10 km. Measurement of heat generation of surface samples is cheaper than drilling for temperature measurements, provided there is access to suitable equipment. Both kinds of measurement are necessary before any further exploration is warranted.

Of the few research projects so far undertaken, all have been aimed at bodies of hard intrusive rock. Such rocks are usually of very low porosity, and permeability is provided only by fractures. It is thus necessary to generate artificial channels for the movement of water through EGS technologies to be able to develop these resources.

There are certainly bodies of hot dry rock within the Cordillera of British Columbia. Meager Mountain, if not exploitable as a hydrothermal system, would qualify as an excellent hot dry rock resource. Other volcanic centres, including Mount Cayley and Mount Edziza, would probably show their own resources. Batholiths show promise, but only two have been examined. The brief experiment in the Coryell intrusives showed that thermal gradients are high enough to be very encouraging. The Cordillera clearly shows the best potential for hot dry rock, because of the young tectonic and volcanic ages. Jessop (2008a) showed that potential in the Maritime Provinces, where intrusive bodies are of Silurian to Devonian age, is much less.

4.2.3a The Coryell Syenite

In 1978, two boreholes were drilled in the Coryell intrusive rocks, to the north of Grand Forks, British Columbia (Lewis et al., 1979). Temperature profiles are shown in Figure 4.5. Both boreholes penetrated water-bearing fractures and provided new paths for water flow. The first hole, shown by the red line, penetrated several fractures, each of which contributed a component to the upward water flow. The second hole, shown by the blue line, penetrated only one fracture that provided upward water flow. Below the water-bearing fractures, temperature gradients were observed to be 51.2 and 54.0 mK/m respectively. These gradients, when multiplied by the average thermal conductivities of 2.13 and 2.18 W/mK respectively, imply a heat flow of about 109 and 117 mW/m^2, and indicate that the high heat generation does indeed extend for some depth.

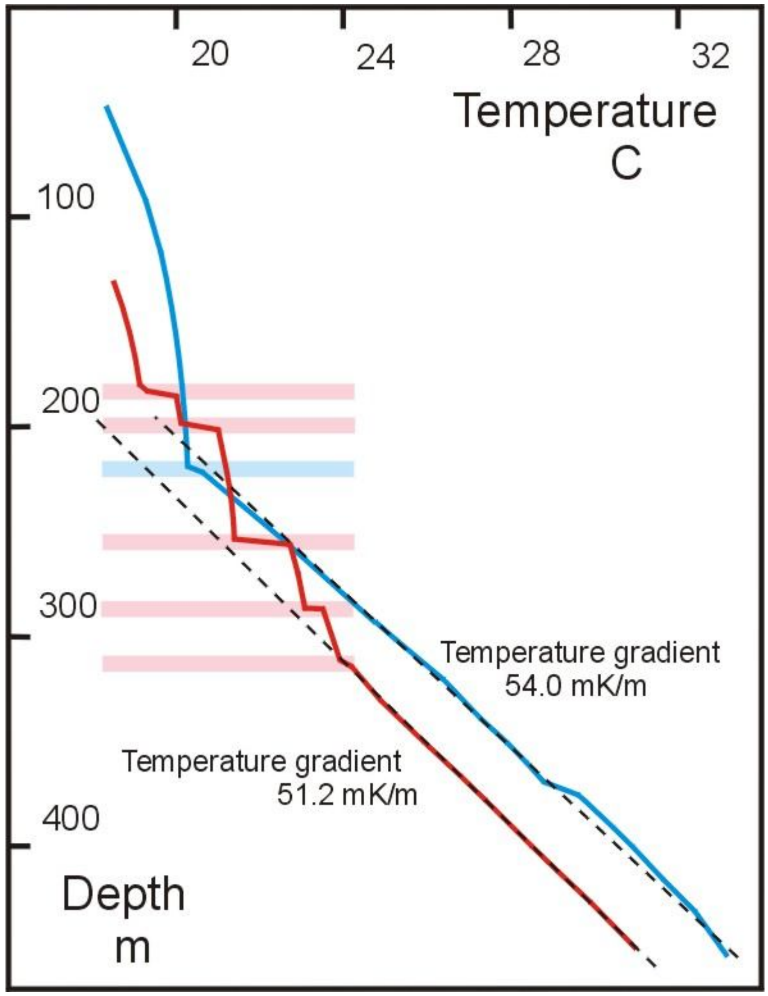


Figure 4.5. Temperature profiles from two boreholes in the Coryell intrusive north of Grand Forks, BC. Temperatures in the upper parts of both boreholes are disturbed by water flow from fractures flowing up the holes, and inflow zones are shown by coloured bars. Below the water bearing fractures thermal gradients are uniform.

The situation in the Coryell pluton is represented best by the red line in Figure 4.5, but it is not clear which line is the most appropriate. It suggests that the temperature of 200 °C is reached at depths of 5,000 m, about the same depth as at Soultz-sous Forêts, France, the location of the current European hot dry rock project.

4.2.3b The Raft Batholith

Four boreholes were drilled into the Raft Batholith in 1984, another rock body that showed a high value of heat generation. Temperature gradients were in range 27.2 to 36.2 mK/m - not as attractive as those observed in the Coryell Intrusives - and average thermal conductivities were 3.18, 2.77, 3.30, and 3.47 W/mK, respectively, giving approximate heat flow of 110, 101, 90, and 108 mW/m^2. This area is probably best represented by the green line in Figure 4.6.

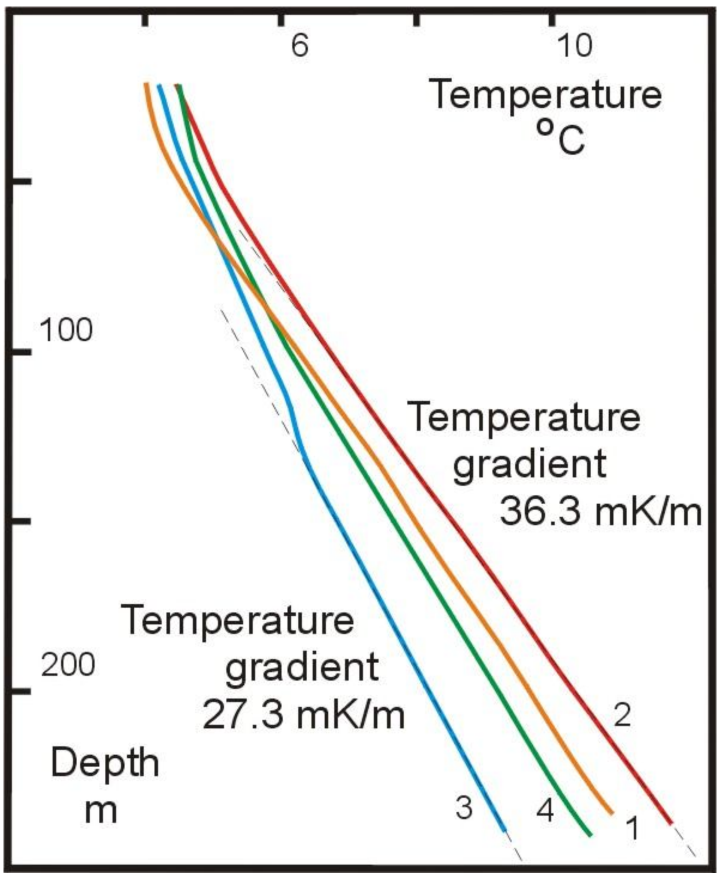


Figure 4.6. Temperature profiles from four boreholes in the Raft Batholith. These profiles show no evidence of disturbance by water flow, except possibly in number 3.

4.2.4 Sedimentary Basins

Geothermal sources in sedimentary basins are of moderate to low temperature. Water is produced through a well that resembles an oil well. Since the water is usually saline, heat is removed through either a simple plate-type heat exchanger or by means of heat pumps. Used water is normally reinjected to the producing aquifer through a second well.

Investigation of the geothermal resources of Canadian sedimentary basins was substantially modelled on the experience in the Paris Basin (Lopez et al., 2010). The normal configuration of wells, used widely used in France, consists of pairs, or "doublets" of wells - one to produce hot water and one to reinject the cooled water. The wells of each pair were drilled within a few metres of each other, but angled so that the separation at the aquifer was of the order of 1 km. This system was designed to provide pressure maintenance in the reservoir and to permit the disposal of potentially harmful brines after use. However, it imposes a finite lifetime on the production of hot water, since the cooled water eventually completes the circuit.

4.2.4a Regina

Early in 1977, the University of Regina approached EMR with the question of a geothermal demonstration project of geothermal water from sedimentary aquifers at the University. A feasibility study, funded by the Geothermal Energy Program, showed that the prospects for geothermal water were good (Vigrass et al., 1978).

The report showed that there were excellent aquifer formations below the study area, each of which could give a good supply of hot water. The best target was a combination of the Winnipeg Formation (depth 2,042 m and thickness 34 m) and the Deadwood Formation (depth 2,088 m and thickness 137 m). Temperatures were predicted to be 71 °C in the Winnipeg Formation and 74 °C in the Deadwood Formation. It was predicted that the water would likely have a high sodium chloride content, probably about four to five times the salinity of sea water, and a low content of hydrogen sulphide.

There were several good reservoirs at shallower depths, including the Interlake Formation (depth 1,825 m and temperature 64 °C), the Winnipegosis Formation (depth 1726 m and temperature 63 °C) and others with temperatures less than 50 °C.

The report concluded that *"Geological and engineering conditions for low-grade geothermal energy are favourable at the University of Regina and, pending the results of other studies, a geothermal research-*

test-demonstration facility is warranted." Supplementary reports included a seismic profile, a seismic data compilation, and an engineering study.

A well was drilled on the campus of the University of Regina in the winter of 1978-79 (Vigrass, 1979). The aquifers in the deeper part of the well were capable of supplying the needs of the sports building that was expected to make use of the heat from the well. Strata depths matched predictions very closely. Salinity was observed to amount to 10 to 12 % dissolved solids by weight, and dissolved hydrogen sulphide was present. Tests showed that the geothermal potential was excellent, the potential flow rates being higher than predicted, but the temperature being lower than expected. The water was saline, roughly four times as saline as sea water, and a reinjection well would have been required to put the water into the formation at a distance sufficiently great to avoid recycling within the lifespan of the system.

It was estimated that water could be produced at 100 m^3/hr at about 60 °C, with a drawdown to 131 m below the surface after seven years. Power requirements for pumping were predicted at 66 kW, about 2 % of the 3.5 MW of heat available, assuming a baseline temperature of 35 °C.

Because of the high salinity and the potential for surface pollution, the used water would have to be returned to the formations from which it came. This would mean the drilling of a reinjection well to put the water into the formation at a distance sufficiently great to avoid recycling within the lifespan of the system.

During the summer of 1979, the Regina well was completed with "open hole" in the Winnipeg and Deadwood Formations, below the casing shoe at 2,034 m depth (Vigrass, 1980). Two six-hour pumping tests were carried out at 100 m^3/hr. Accurate temperature measurement showed that water temperature was about 60 °C. Drawdown was calculated to reach 222 m below ground level after 2,500 days.

Unfortunately, the large sports building that was intended to be the load for the well was not built, and the remainder of the campus uses a steam heating system, and so the well has never been used for its intended purpose. However, it has been used as a research facility, for temperature logging, hydrofracture testing, water level monitoring and corrosion testing. It had thus been of great value to the Geothermal Energy Program, in a manner that was not originally intended.

4.2.4b Moose Jaw

After the drilling of the well at the University of Regina, the City of Moose Jaw expressed interest in restoring the water source for the Natatorium. From 1933 to 1957 the "Natatorium" had been fed with warm saline water from a deep well, originally drilled for gas exploration. The Natatorium was an attraction to both the local population and to tourists. The water was described as *"rich in sodium chloride, sodium sulphate and magnesium sulphate, comparable with the waters of Carlsbad and the more notable German curative springs"* (Moose Jaw Times Herald, 10 June 1933). The same report also stated *"visitors from all over the dominion and many points south of the border have been loud in their praises of the hot mineral water with which the pool is supplied"*. Eventually the old wooden casing of the well collapsed and the supply of warm water was cut off. After 1957 the geothermal water was replaced by surface water, heated with natural gas, and chlorinated for health reasons.

EMR contracted a study of the feasibility of restoring the water supply and of other possible uses for the water or the heat. Acres International Ltd. (1985) reviewed the aquifer formations below the City of Moose Jaw that are capable of providing a source of water and the potential for retrofitting existing buildings to make use of the energy resource. Four possible schemes of geothermal exploitation were presented. Each scheme associated the total demand of the proposed users with the volume and temperature of the geothermal water, and hence with pumping requirements and depth of drilling. It was concluded that the smaller schemes, associating retrofit of a few close buildings with the renewed Natatorium, offered the best prospects for economic use of a geothermal resource. Larger schemes, involving retrofit of more buildings over a wider area were judged to be best left until some operational experience had been gained.

It was found that the initial cost of drilling the two wells required, one to produce and one to reinject the water, was a major part of the total cost, and that the pair of wells could provide an energy supply for a wide range of existing buildings in the centre of the city. Seventeen potential users were identified, including municipal and commercial buildings, mostly within an area of four by five city blocks.

In the autumn of 1989 two wells were drilled to the Birdbear Formation. One of them had a temperature of 53.1 °C at 1352 m depth. A temperature log of one of the wells is shown in Figure 4.7. Pressure in the wells was such that an open well would produce a fountain about 20 m high. This means that reinjection would require high pump pressures.

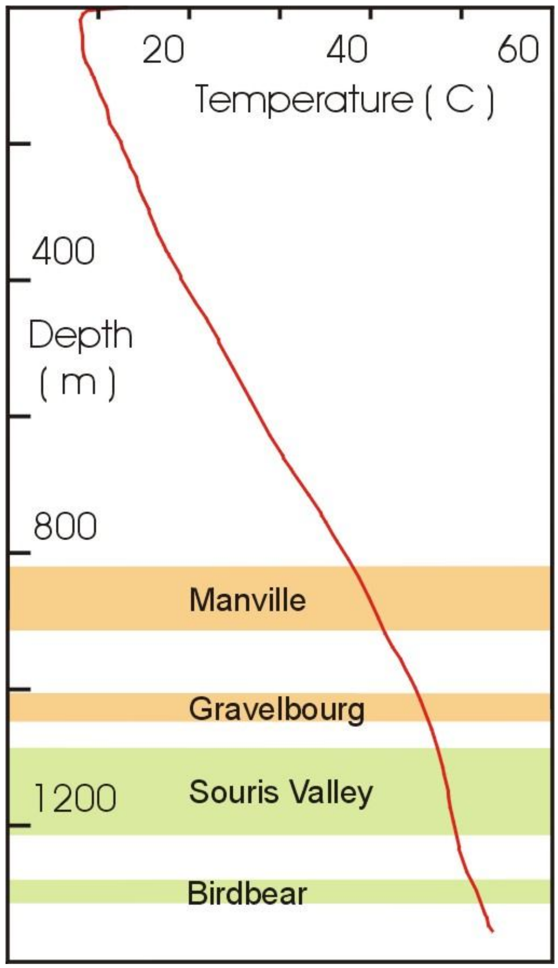


Figure 4.7. Temperatures in one of the wells at Moose Jaw, with aquifer formations. Orange colour shows sandstone aquifers and green shows limestone.

4.3 ABANDONED MINES

Research into very shallow geothermal applications, or ground-source heat pump systems, was not part of the mandate of the Geothermal Energy Program. However, late in the life of the Geothermal Energy Program a request from the Town of Springhill led to investigations into the use of water from abandoned mines. Old mines provide a large reservoir of water. In the case of the Springhill mines, the water was obviously mixing and convecting within the mines, and the temperature near the surface was about 19 °C. Water at this temperature, and in the quantities that could be produced from the mines was clearly an excellent source.

Springhill had been a major coal-mining centre until rock bursts forced the closure of the mines in 1958. The mine workings went to a depth of 1,323 m. By 1984 they were flooded. Water in the mines was circulating by convection and the temperature was much higher than the normal ground temperature of about 6 °C to 8 °C. The industrial buildings of the town were almost all overtop the mine workings. It was proposed by John M. Booth Engineering Ltd. that boreholes into the mine workings could bring up the warm water, which could be run through heat pumps and returned to the mines by a second borehole.

John M. Booth Engineering Ltd. (1985) showed that there were at least 25 buildings that could benefit from geothermal heating. Energy costs would be about 40 % of the costs of oil heating. Capital payback times would be from four to six years for heating systems and better than two years for systems delivering both heating and cooling. The report concluded that the concept of geothermal heating was technically feasible and could be a valuable incentive for industries to open in Springhill.

Jessop et al. (1995) showed that the total volume of water in the mines was about 4×10^{6} m^3, based on the assumption that collapse had occurred to fill 75 % of the mined space. Analysis of data of input and output temperatures of the system in place at Can Am Ropak Ltd showed that the building was putting more heat into the mine reservoir in summer than it was taking out in the winter. However, this plant is involved in plastic moulding, and thus produces a great deal of heat. The mine-water system was acting as a heat balancing system at a low cost. The mine-water system had the added advantage that it reduced carbon dioxide emissions by about 50 % from conventional sources of energy. Other buildings would be expected to take more heat in winter than they returned in summer, but since the resource is so large and convectively renewable, it could be regarded as indefinitely renewable.

Because of the success of the pioneer work of the Town of Springhill in the use of mine water and heat pumps for heating industrial buildings, an investigation into the sources of information about abandoned mines was conducted. Katherine Arkay Consulting (1992) showed that there are many abandoned mines in all provinces of Canada, and the Provinces of Quebec and Nova Scotia were used as the model for a system of search and data record. The report includes the design of a data form, which includes the questions of location and size of the mine, possible temperature of the water, and proximity to potential users. Information on the mines is to be found in provincial records. Data were included of about 160 old mines in Quebec and 400 mines in Nova Scotia.

4.3 RESEARCH POST 1986

Since the end of the Geothermal Energy Program in 1986 research has continued on a small scale as funding permitted. A request for a research project from the Corporation of the District of Summerland in 1986 had to be denied, but a few years later the GSC, in co-operation with the BC Department of Energy, Mines and Petroleum Resources (DEMPR) was able to drill a diamond drill hole to investigate the possibility of warm water for the heating of greenhouses within the town of Summerland. The local agency promoting the project was the Okanagan-Similkameen Community Futures Association (OSCFA).

The chosen site was about 1 km to the northwest of the centre of the town, close to a potential user. At this point the well was expected to reach the base of the Tertiary volcanic rocks and penetrate aquifer rocks. The well was drilled over a period of two years to a total depth of 956 m, which was the limit of the equipment available, but it failed to intersect any aquifer. Temperature reached 41 °C, more than adequate for the purpose proposed, but the lack of water made the project a failure. A temperature gradient of 33 mK/m over most of the well showed that similar ventures in different locations in the Okanagan Valley might be more rewarding.

5. CANADIAN GEOTHERMAL RESOURCES

5.1 INTRODUCTION

While the geothermal resource base has been well known for years following initial work under the Geothermal Energy Program (Chapter 4), the resource has not been clearly defined on a national scale. This section examines various geoscience aspects that can help define geothermal resource potential and regions in Canada with the most favourable geological conditions for economic production of geothermal energy (based on current technology).

5.2 HEAT FLOW

Variation in heat flow to the Earth's surface can provide an initial assessment of the geothermal potential. Previous heat flow maps have been constructed for North America (Blackwell and Richards, 2004), with the Canadian portion based on initial heat flow compilations by numerous workers (Jessop et al., 1984a, 2005; Majorowicz and Jessop, 1981a, 1981b; Majorowicz 1996; Majorowicz et al. 1985; Majorowicz et al. 1999; Majorowicz et al. 1988; Majorowicz et al. 1996; Majorowicz and Embry 1998; Lewis 1991; Lewis et al., 2003; Geotop, 2009; Jessop, 1990a; Jessop et al., 2005; Jessop et al., 1984a, 1984b). The resultant database, consisting of 3,085 heat flow measurement locations, allows assessment of the regional variability of average heat flow in Canada. The distribution of available heat flow data, shown in Figure 5.1, illustrates that there are large regions of Canada with sparse or no data.

To better honour data constraints on the maps prepared for this chapter, extrapolated surfaces were limited to 50 km contours surrounding each data point. In addition, new smoothing and averaging techniques were used which filter out anomalous data. Averaging of values was done using the averaging program of M. Webring (see Cordell et al., 1992) for a 48 km radius on a 4 x 4 km grid. As a result, estimated heat flow values are available for only 40% of Canada's landmass (Fig. 5.2), whereas the remainder (in white on all maps) is unknown due to lack of data.

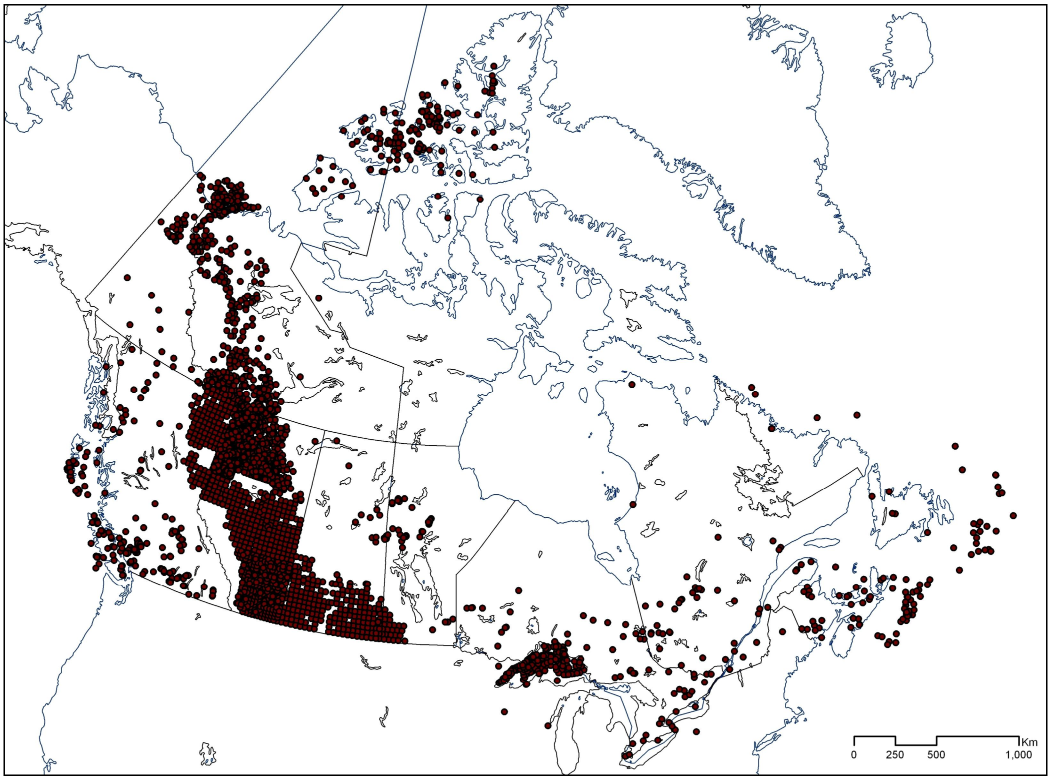


Figure 5.1. Map of data points for heat flow measurements across Canada.

Overall, the heat flow values in the Canadian Cordillera are similar to the western US Basin and Range areas (Blackwell, 2006). This is especially true for extensional areas like the Ominica Belt in southern British Columbia. Other regions of very high heat flow (>70 mW/m^2) occur in parts of the Western Canada Sedimentary Basin (WCSB), particularly in northwestern Alberta, northeastern British Columbia, southwestern Northwest Territories, and the southern Yukon. Heat flow in these areas range from 70 to 120 mW/m^2. High heat flow values of >70 mW/m^2 are also found in the Mackenzie Corridor, in the foreland basins of the Northwest Territories, and in the eastern part of the Tuktoyaktuk Peninsula in the Beaufort-Mackenzie area. High heat flow is also observed in shallow parts of the WCSB in southeastern Saskatchewan (Weyburn area) and southwestern Manitoba, and also in the Lac LaBiche area (>70 mW/m^2). Elevated heat flow is also observed in the Appalachian region in Eastern Canada (>60 mW/m^2).

Figure 5.2 shows elevated heat flow in passive margin basins of the Atlantic. These areas, however, are of lesser interest for geothermal development as the high heat flow areas are under water. In general, high heat flow regions in Canada's High Arctic are in areas with little or no population, and temperatures are depressed due to thick ice-bearing permafrost. The base of permafrost, which constrains temperatures to 0 °C, extends from ~0.2 to 1 km depth. However, there are some isolated communities (e.g. Resolute Bay) near high heat flow areas, which are dependent on diesel for all their energy needs, that may benefit from a local geothermal resource base. The national average heat flow, as calculated based on Figure 5.2, is 64 $mW/m^2 \pm 16\ mW/m^2$. However, regional heat flow varies from values as low as 20 to 30 mW/m^2 in the Canadian Shield of central Canada to highs in the northern Canadian Cordillera reaching >100 mW/m^2.

High variability in heat flow values is driven by variability in heat generation of the upper crust (highest in the crystalline rocks like granites), and mantle heat from below. The amount of 'reduced' heat flow (Q_r), which characterises heat under the upper crystalline crust, is lower for the cratonic areas, especially in the Canadian Shield. Much higher vertical heat flow (from the mantle) occurs in younger orogenic belts of the Canadian Cordillera According to Jessop (1990) the average cratonic and orogenic belt heat flows are 30 and 60 mW/m^2 respectively. The highest heat flow values measured in Canada occur in the Garibaldi volcanic belt (>200 mW/m^2). These systems are not purely conductive and available temperature logs are disturbed by movement of hot water or vapour (see Jessop et al., 1991 for references), and are characteristic of a local heat flow zone related to a back-arc system. While recognizing that these local high heat flow values indicate areas of significant local geothermal potential, the mapping methods used in the current study avoid these local anomalies so as not to give a false indication of high regional heat flow. As such these highest values were excluded for regional mapping purposes.

5.3 GEOTHERMAL GRADIENTS AND THERMAL CONDUCTIVITY

Here we examine variability in geothermal gradients determined from measured temperature records across Canada. In addition, we examine variations in thermal conductivity, from measured data and from estimates of effective conduction in sedimentary basins that are based on measured rock averages and net rock analysis. Knowledge of geothermal gradients is important to be able to conduct first order estimates of temperature variations with depth, in the upper several kilometres that are feasible for geothermal energy development. Thermal conductivity, K, of rocks is an important parameter that allows evaluation of heat transfer between the heat source and the heat sink. It is an intrinsic part of the estimation of thermal diffusivity, κ

$$\kappa = (K/\rho c) \tag{5.1}$$

where K = thermal conductivity (W/m K), ρ = rock density (kg/m^3) and c = heat capacity (J/kg.K). Thermal diffusivity estimates are needed for modelling time-related heat transfer and the long term sustainability of the geothermal resources during exploitation for energy.

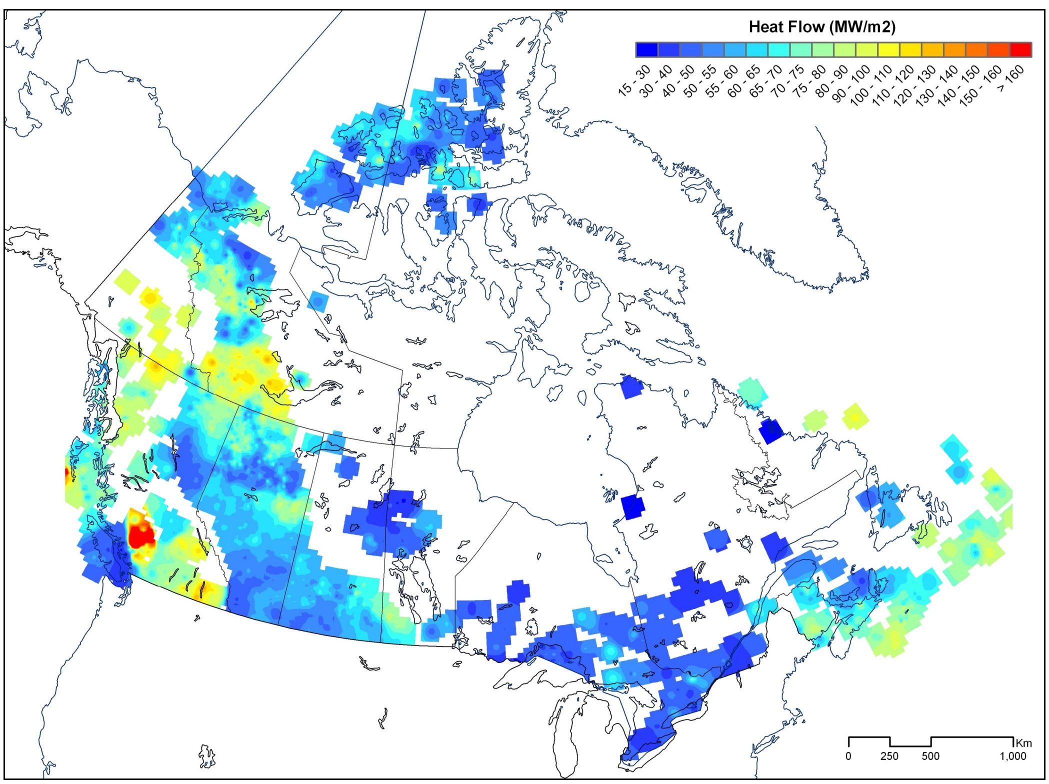


Figure 5.2. Heat flow map of Canada.

The thermal conductivity of rock is an important parameter for geothermal development. However, it is often not possible to measure the thermal conductivity of the rocks in deep strata. Few cores are available from boreholes to allow for direct measurements of thermal conductivity in a laboratory, so the usual approach is to calculate thermal conductivity based on factors including lithology and porosity. Accurate estimates of thermal conductivity are important for depth-temperature (geotherm) modelling using known surface heat flow for depths where measured temperatures are not available. Data compilations for geothermal gradient, heat flow and thermal conductivity were published for all of Canada (Jessop et al., 1984a; Jessop et al., 2005), and for western and northern Canada (Lewis, 1991; Majorowicz et al., 1985; 1988; 1996; 1999).

Thermal conductivity of individual rocks types from the upper crust (crystalline and sedimentary successions) are available in Canadian and American compilations for the Shield, Appalachians and Cordillera (Jessop, 1990; Jessop et al., 2005; Drury, 1986) and the WCSB and eastern and northern Canadian sedimentary basins (Majorowicz and Jessop, 1981b; Roy et al., 1981; Reiter and Tovar, 1982; Reiter and Jessop, 1985; Beach et al., 1987). A typical thermal conductivity for crystalline rocks is 3.2 W/m K (Jessop, 1990b) while a lower 2 W/mK is for sedimentary rocks (Barker, 1996).

Knowledge of the 'net rock' porosity and component rock conductivity K_i at depth allows calculation of the continuous K-depth variations and temperature–depth variations, both of which are important for calculation of the geothermal state of the target reservoirs. Predicted temperature at depth is:

$$T = T_o + Q\,(\Sigma(_{i=1..n}\,(D_i/K_i)) \qquad (5.2)$$

where T_o is surface temperature (at 20 m depth), Q is vertical heat flow, and D_i is thickness of the layers (i = 1...n). In Canada, T_o (surface temperature) is usually assumed to be near -1 °C to 0 °C and that deep (>2 km) temperatures are in equilibrium with that. For the case of shallower depths, in the upper few hundred metres, it is assumed that temperature is in equilibrium with mean annual ground surface temperature (see Majorowicz et al., 2009).

An example of predicted variation of temperature with depth (from northeastern British Columbia), based on regional heat flow, estimated thermal conductivity variations with depth, and surface temperature, is shown in Figure 5.3.

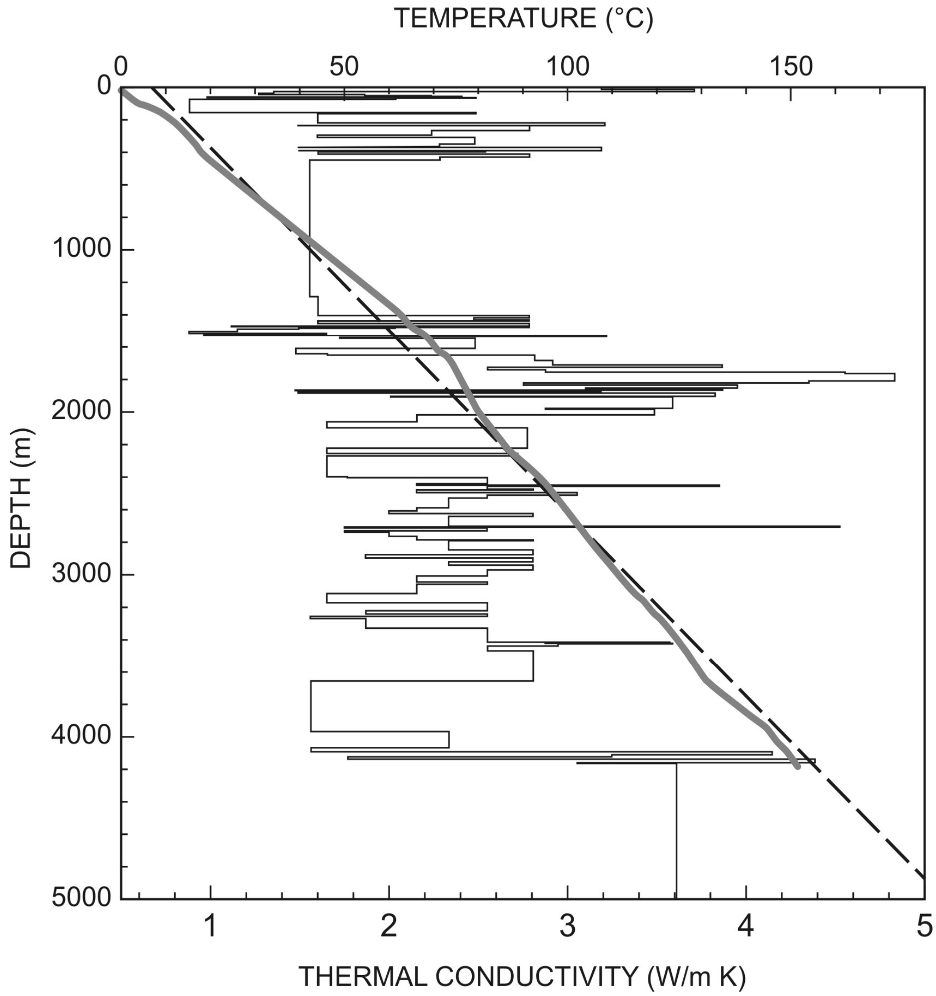


Figure 5.3. Example of the variation of thermal conductivity with depth in northeaster British Columbia (in the NW part of the WCSB), and the related thermal gradient variation. The thin jagged solid black line represents variation of thermal conductivity with depth; the thick grey line is the computed gradient for a heat flow of 70 mW/m^2 (typical of the study area) and the illustrated thermal conductivity profile; the dashed black line is least squares approximation of the computed thermogram. Source: Majorowicz et al. (2005).

The vertical component of the thermal gradient (dT/dz) can be estimated from high precision depth-temperature logs and additionally from lower quality point measurements (bottom hole temperatures, drill stem test temperatures, etc.) that are available from petroleum and mining industry drilling reports.

These provide valuable information on the temperature distribution in sedimentary basins, the Shield, and mountain belts in Canada.

Table 5.1: Typical values of thermal conductivity (in W/m K) of rocks in Canada.

Lithology	**Source[1]**	**Source[2]**	**Source[3]**	**Source[4]**	**Source[5]**	**Source[6]**	**Source[7]**	**Source[8]**
Sandstone	2.8	4.2±1.4	3.1±1.3	3.7±1.2		3.7±1.2		4.7±2.8
Claystone			2					1.8
Mudstone						2.0±0.4		1.9±0.4
Shale	1.5±0.5	1.4±0.4	2.1±0.4	1.4		2.1±0.4		1.8±1.2
Siltstone	2.7±0.9	3.2±1.3	2.7±0.2	2.7±0.9		2.7±0.2		
Limestone	2.9±0.9	2.4±0.9	2.8±0.4		3.4±3.0	2.8±0.3		2.5±0.6
Marl	2.1±0.7	3.0±1.1	2.7±0.5					2.4±0.5
Dolomite	5.0±0.6	3.1±1.4	4.7±0.8		4.8±1.5	4.7±1.1		3.7±1.8
Halite	5.5±1.8	5.7±1.0	5.4±1.0			5.4±0.3		5.9
Chert	4.2±1.5	1.4±0.5	1.4±0.5					
Quartzite					5.0±2.4	5.9±0.8		5.6±1.9
Granite					3.4±1.2		3.5±0.4	2.8±0.6
Basalt					1.7±0.6		2.0±0.2	1.5
Conglomerate	2.4±0.8	3.2±1.8	2.1±1.0					
Coal	0.3±0.1	0.2±0.2	0.2±0.1	0.3±0.1				
Loose sand								
Typical sediment		2.3±2.0						

Source: [1] Beardsmore (1996)); [2] Beach et al. (1987); [3] Reiter and Jessop (1985); [4] Reiter and Jessop (1985) and Reiter and Jessop, 1985; [5] Roy et al. (1981); [6] Reiter and Tovar (1982); [7] Drury (1986); [8] Barker (1996)

The vertical component of heat flow, Q, and thermal conductivity, K, are linked by the Q/K relationship for any depth along the "z" axis of the well following Fourier's law (Jessop, 1990b):

$$Q = -K \ \delta T / \delta z \qquad (5.3)$$

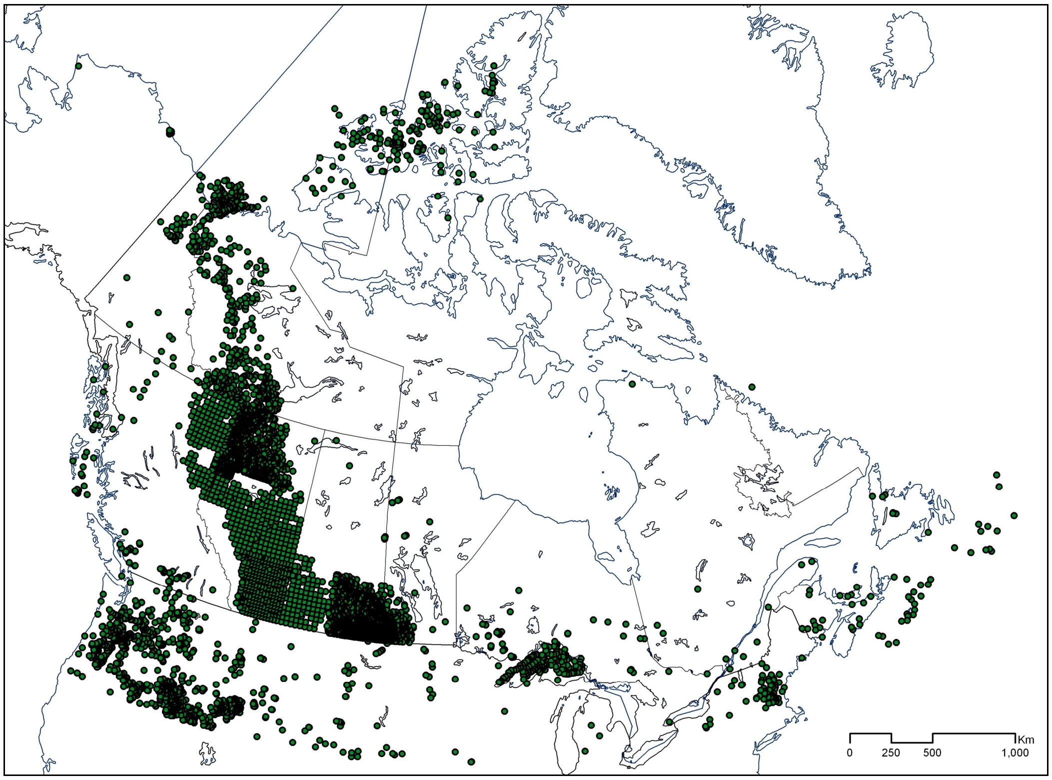
where: $\delta T/\delta z$ is thermal (temperature) gradient. It is usually assumed that the vertical component of the heat flow is constant (Q=constant), the conductive strata are horizontal and parallel, and that heat flows only by conduction.

Usually, thermal gradients are highly variable due to differences of lithology and porosity, showing related variability in thermal conductivity with depth (Fig. 5.3); therefore, a mean geothermal gradient is reported. Such values are used to construct maps of geothermal gradient patterns. In most cases, these linear approximations are practical, as shown in Figure 5.3 by the comparison of the thermal conductivity variation related temperature-depth model, and the linear approximation of temperature variation with depth. This allows an approximate temperature at any depth to be predicted beyond depth intervals where temperature measurements are available.

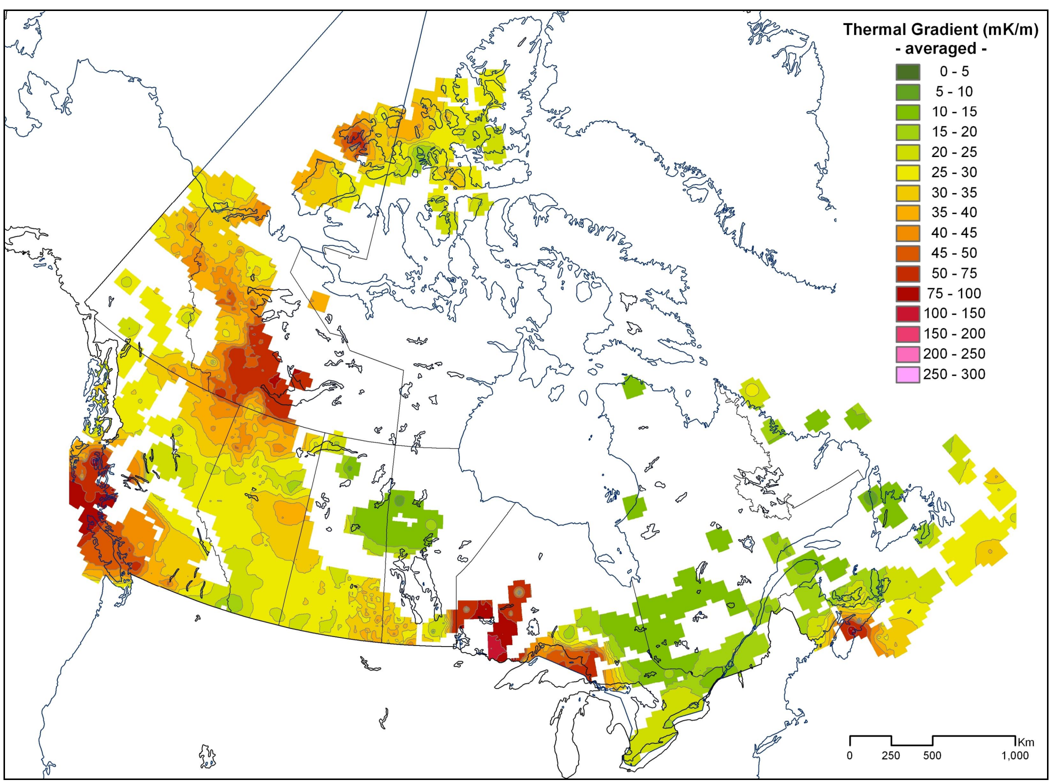
The map of geothermal gradient across Canada is based on the data compiled for the locations shown in Figures 5.4a. Data south of the Canada-US border were taken into account in the contouring procedures (averaging in grid space) in order to avoid a border effect. The data for the US were acquired from the International Heat Flow Commission (IHFC; 2010) database.

Geothermal gradient values range from 0.5 -250 °C/km across Canada (Fig. 5.4b). The highest geothermal gradient values are for the volcanic belts in British Columbia (Lewis, 1991; Lewis et al., 2003; Hyndman and Lewis, 1999), particularly in the southwestern part of the Canadian Cordillera (back-arc areas) and in the northern parts of the WCSB (>40 ^{o}C/km). The lowest geothermal gradients are in the Canadian Shield. Some local high gradient areas are also observed in the Atlantic Canada and parts of Beaufort-Mackenzie and Arctic Island basins. High thermal gradients in the WCSB in northeastern British Columbia and the southern parts of the Mackenzie Corridor are due to a combination of relatively high heat flow (some 90 mW/m^2) and a low thermal conductivity thermal blanket (<2 W/m K). High geothermal gradients in the Great Lakes basin are mainly due to the very low thermal conductivity of shallow lake sediments (as discussed below) and do not form important geothermal energy resources as compared to Western Canada and Atlantic Canada.

a)


Km
0 250 500 1,000

b)


Thermal Gradient (mK/m)
- averaged -
0 - 5
5 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50
50 - 75
75 - 100
100 - 150
150 - 200
200 - 250
250 - 300
Km
0 250 500 1,000

c)

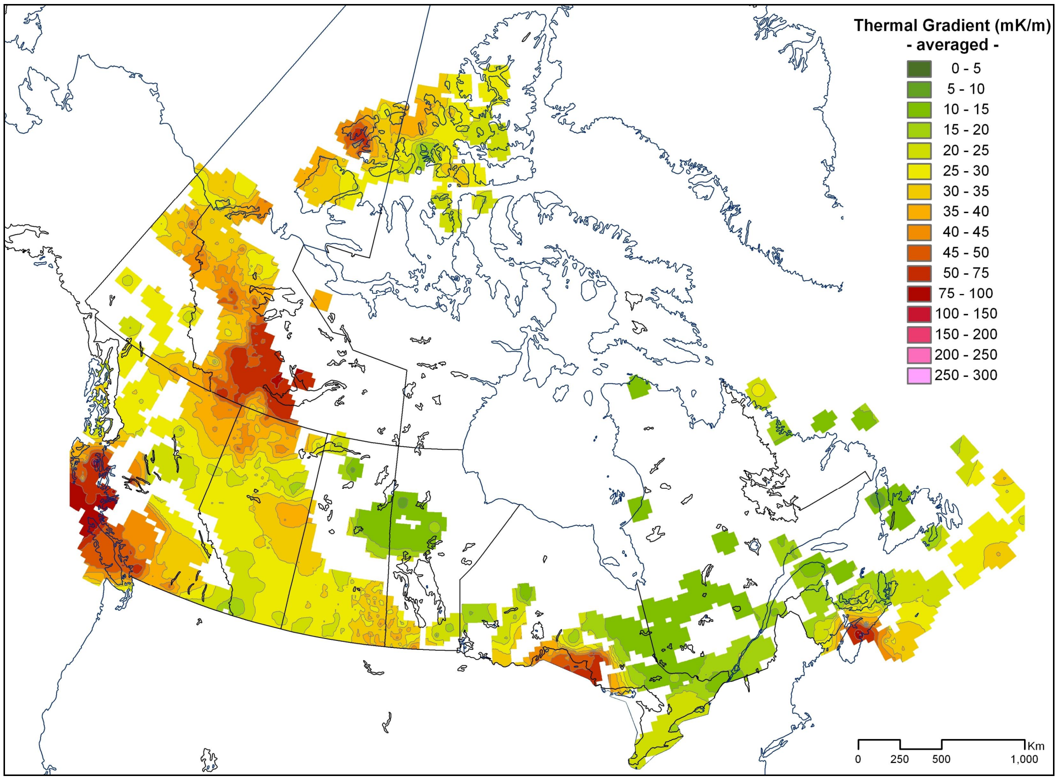


Figure 5.4 Geothermal gradient data in Canada a) Location of data points with geothermal gradient data. b) Contour map of the geothermal gradient (°C/km), including shallow lake measurements in Western Ontario by Allis and Garland (1979); c) contour map of the geothermal gradient without shallow lake measurements.

Allis and Garland's (1979) heat flow determinations in shallow lakes give very high values which affect contours of geothermal gradients in northwestern Ontario. Many of the heat flows exceed values that would be expected by applying the heat flow-heat production relationship for expected heat production values. Measured heat production of about 3.4 microwatts per cubic meter in granite in northern Minnesota (Gosnold, personal Comm. 2010) would produce heat flow of only 55 mW/m^2. This makes values > 70 mK/m doubtful. For example, the point in the International Heat Flow (IHFC 2010) database in southwestern Ontario has a gradient of 233 mK/m and a conductivity of 0.69 W/m/K, which causes the high thermal anomaly in Figure 5.4b. Gosnold, W. (personal Comm. 2010) measured five new geothermal gradients in the Precambrian granites in NE Minnesota, at sites close to Ontario. At borehole depths of 400 to 600 m, the gradients range from 10 to 15 mK/m (°C/km). Due to spurious effects of lake sediments, the map without these values is thought to be a more valid representation (Fig. 5.4c) than the map which includes these values (Fig. 5.4b).

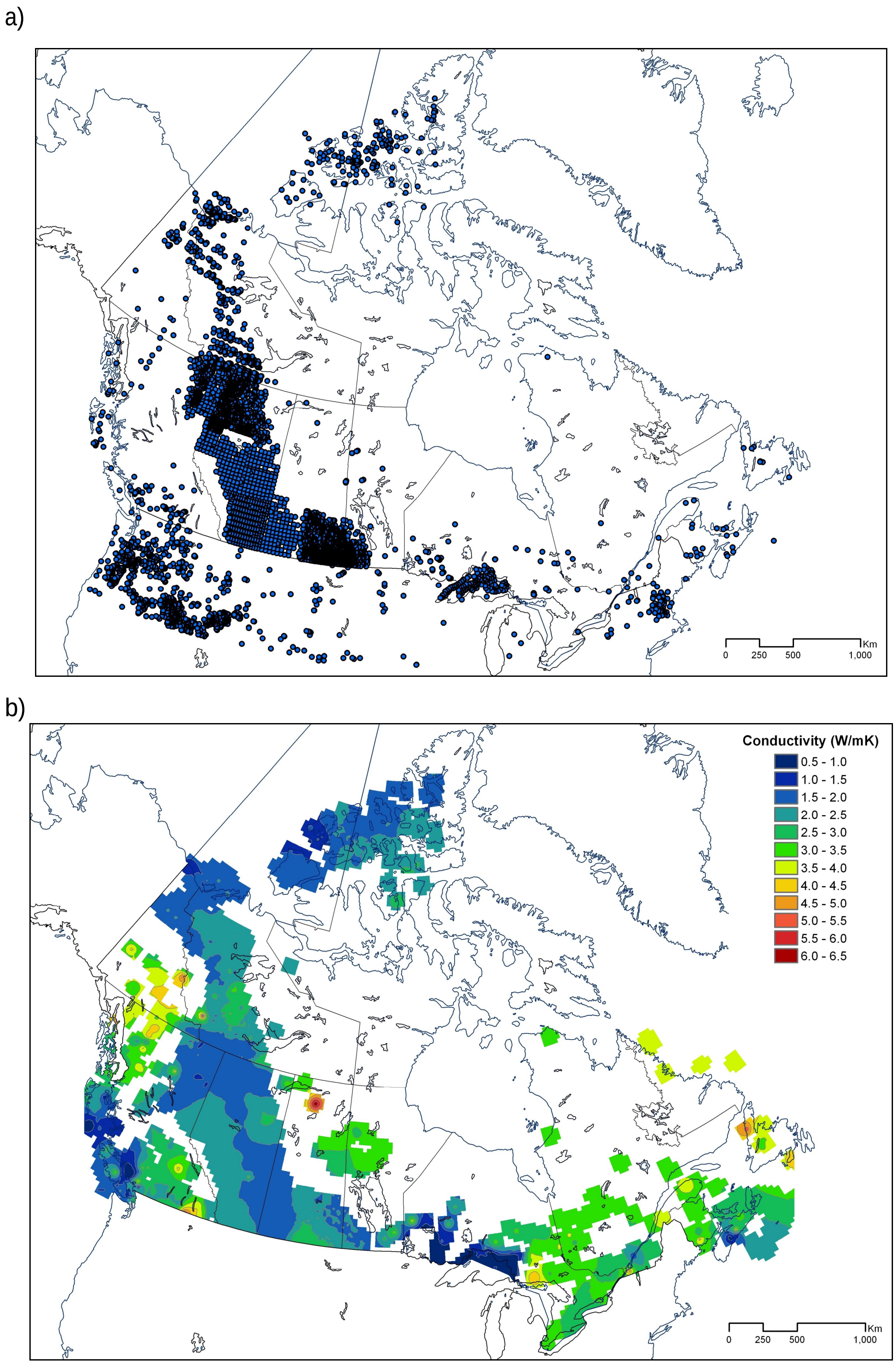


Figure 5.5. Thermal conductivity data in Canada. a) Locations of data points with thermal conductivity data; b) Pattern of the mean thermal conductivity (W/m K) across Canada.

The map of thermal conductivity across Canada is based on the data compiled for the locations shown in Figure 5.5a. The contour map of mean thermal conductivity (W/mK) is shown in Figure 5.5b. This map is based on measured conductivity values from boreholes with core or rock chips data (these are reported in Jessop et al., 2005 and other Canadian heat flow publications listed above) and estimates of effective thermal conductivity in sedimentary basins. The latter are based on averages of typical thermal conductivity of rocks (see Table 5.1) and net rock data (see explanations in Majorowicz et al., 1985).

The lowest thermal conductivity values are for lake sediments (Allis and Garland, 1979) and the highest are for the crystalline rocks, with values ranging from 0.5 to 6.5 W/m K. The variations in thermal conductivity determine, to a large extent, prospects for high temperatures, which are needed in low and high enthalpy geothermal energy development. Low thermal conductivity rocks (2 W/m K or lower), observed mainly in Canadian sedimentary basins, create a thermal blanketing effect which is essential for the potential of these basins for geothermal energy use. High thermal conductivity areas are found mainly in the Canadian Shield, the Canadian Cordillera, and Paleozoic orogenic belts. High conductivity values in Shield rocks (3-4 W/mK) together with its low heat flow (~ 40 mW/m^2), create low thermal gradients and low geothermal energy prospects.

Geothermal gradients and thermal conductivity values for Canada show very high regional and local variability, as seen by the histograms of mean thermal gradient (Fig. 5.6) and mean thermal conductivity (Fig. 5.7). Despite the high variability, general patterns of spatial variability of thermal conductivity and thermal gradients emerge (Figs. 5.4 and 5.5) and can be related to the major geological provinces (Cordillera orogenic belts, sedimentary basins, Canadian Shield, Appalachians, and the continental margins). The high variability of thermal conductivity and thermal gradients is interlinked, because for a given rock thermal conductivity, the thermal gradient is controlled by deep heat flow related to thermal sources (radiogenic in the crust and transient post-orogenic energy from mantle). That is, for a given heat flow, the thermal gradient depends on thermal conductivity (reverse relationship).

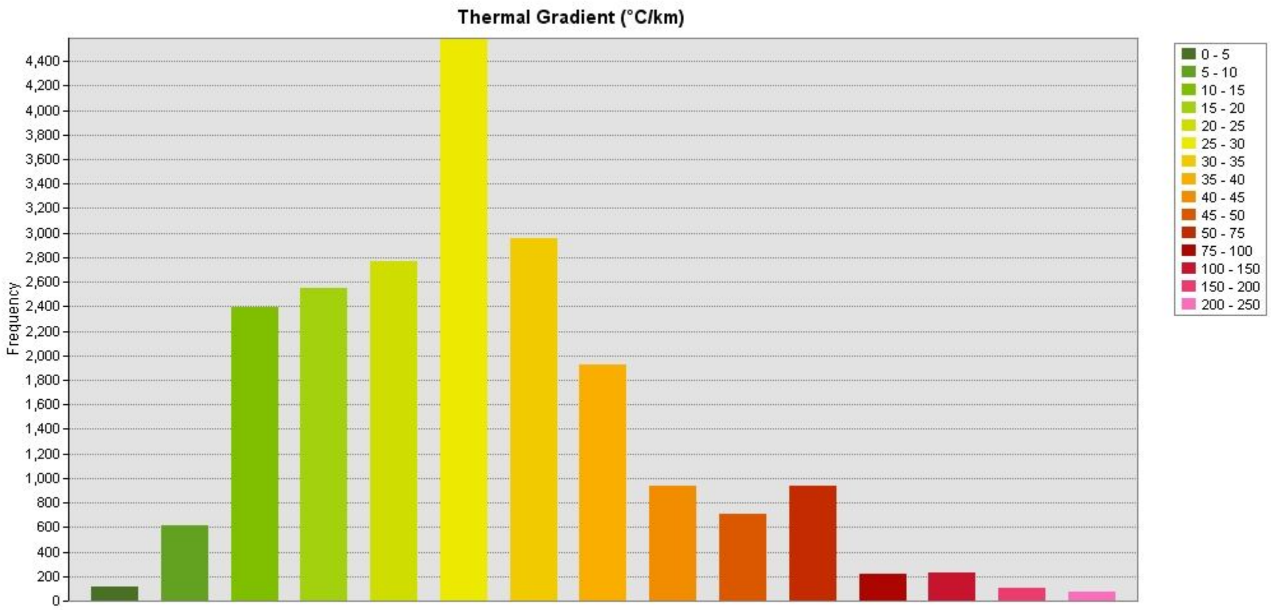


Figure 5.6. Histogram of thermal gradient (°C/km) across Canada based on gridded values used to produce maps (Fig. 5.4).

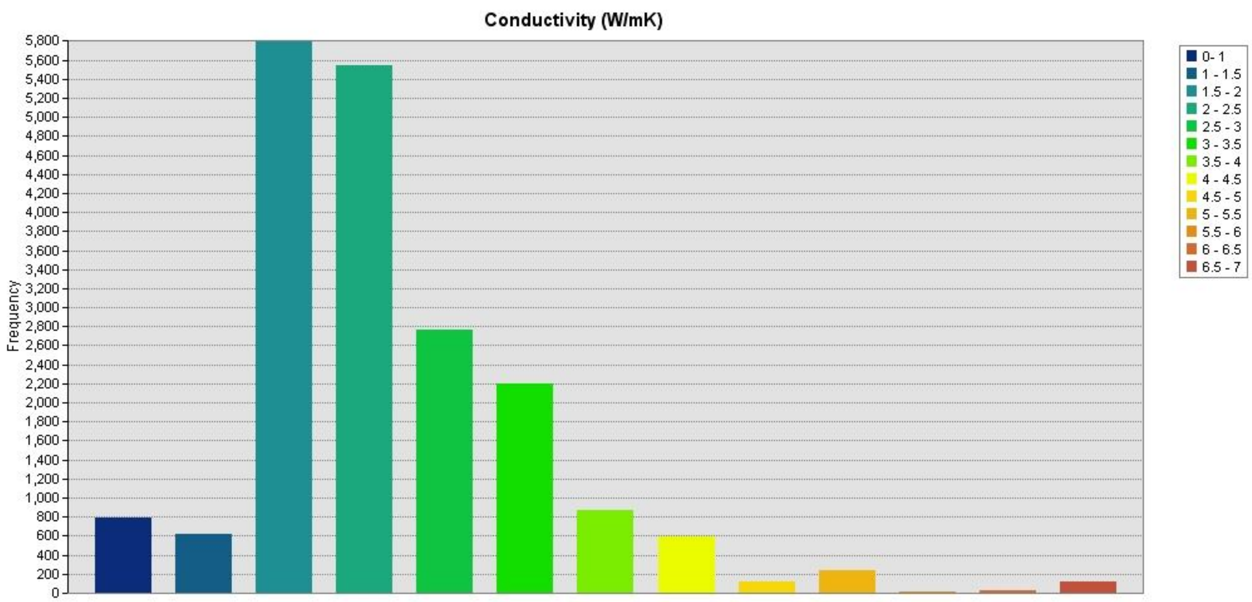


Figure 5.7. Histogram of thermal conductivity (W/mK) across Canada based on gridded data for Canada used to produce maps (Fig. 5.5).

5.4 DEPTH-TEMPERATURE MAPS – DEEP SYSTEMS

The heat flow map in Figure 5.2 is the basis for modelling of temperatures for different heat flow - heat generation provinces at depths of 3.5, 6.5, and 10 km (Figs. 5.8-5.10). These depths are chosen for consistency with depth-temperature maps for the US (Tester et al., 2006) and discussed by Blackwell (2006) and Blackwell et al. (2007).

For depths where no measured data are available, heat flow maps are used for calculating temperature, as discussed below. There is an established statistical relationship between heat flow (Q_o), heat generation (A), and thermal conductivity (K) that can be used to calculate temperature at depth (Jessop, 1990b; Lachenbruch, 1971; Blackwell, 2006; Drury, 1988). Heat flow values are available for locations shown in Figure 5.1 and estimated average values of thermal conductivity for sediments and crystalline rocks (Table 5.1) are derived as described above. Knowledge of near-surface temperatures (derived from depth temperature logs), and calculated temperatures at the top of Precambrian (in the case of areas overlain by sedimentary cover), permits calculation of temperature profiles for the upper parts of crystalline crust below sedimentary basins. The variation of temperature with depth in the crystalline crust can be calculated by the 'Lachenbruch model' of exponential decrease of crustal heat generation with depth. This model (Lachenbruch, 1970; 1971) is the only possible model able to explain the heat flow/heat generation relationship in cases of significant upper crustal erosion. The relationship is in the form (Roy et al., 1968):

$$Q_o = Q_r + DA_o \qquad (5.4)$$

where basement heat flow, Q_o (W/m^2) is correlated statistically with heat generation of the basement, A_o (W/m^3). Here, both Q_r, the reduced (deep) heat flow (W/m^2) and D measured in units of depth, are constants characteristic of large geological provinces. Temperature (T) vs. depth (z) is calculated from the equation:

$$T(z) = T_b + Q_r z K^{-1} + A_o D^2 K^{-1}(1-\exp(-z/D)) \qquad (5.5)$$

where T_b is the temperature at the crystalline basement surface, z is depth, K is the thermal conductivity, and D is the slope of the empirical/statistically derived heat flow (Q) vs. heat generation

(Ao) relation, where Ao is surface heat generation of the crystalline basement. This model was applied to the Canadian land mass because good heat flow –heat generation statistical relationships were established for all of the major Canadian provinces, similar to that in the US (see review in Jessop, 1990b).

Thermal conductivity (K) for the crust and upper mantle for Canada is from Jessop (1990b). Typically, thermal conductivity for crystalline rocks is 3.2 W/m K, whereas a lower value of 2 W/m K is used for sedimentary rock. Typical heat generation values for Canada are A_o= 1 to 5 μW/m^3 for the low and high heat flow regions, respectively, based on existing data from Canada (Burwash and Burwash, 1989; Drury, 1986; Jones and Majorowicz, 1987; Jessop, 1990b; Lewis et al., 2003). The parameters used to construct maps of temperature fields at 3.5, 6.5, and 10 km for major heat flow provinces of Canada are provided in Table 5.2.

Table 5.2. Key parameters used to estimate depth-temperature relationships for main geological regions of Canada.

Region	D (km)	Q_r (mW/m^2)	A (μW/m^3)	K (W/mK)
Craton	9.6	33	1.7-3.7	1.8-3.4
Shield	8-10	33	0.9-2.6	2.6-3.4
Atlantic	8-12	40	1.6-2.3	2.6-3.4
Cordillera	10	50 - 60	2.0-5.0	2.6-3.4

As described above, heat flow patterns are used to calculate depth-temperature profiles at depths beyond which physical measurements have been made. There are uncertainties in heat flow (here we show the calculations for a 10 mW/m^2 error). There is also uncertainty in the temperature of the basement below the sedimentary cover. Large uncertainties for the WCSB are due to the fact that the heat flow –heat generation relationship for the crystalline basement underlying the sedimentary basin had to be derived from equivalent Precambrian-Archean rocks exposed at surface to the east. Surface temperature control is well known and mapped for all of Canada (Grasby et al., 2009).

The temperatures at depths of 3.5, 6.5, and 10 km are shown in Figures 5.8 to 5.10. Data points, as shown in Figure 5.1, are the same for all maps. Analysis of these maps shows that temperatures suitable for geothermal electrical generation (>150 ^{o}C) can be reached over large areas of Canada. Overall, temperatures are highest in western Canada, reaching 150 °C at depths of 3.5 km in limited areas of the Canadian Cordillera, and in the southern part of the Mackenzie Corridor (Fig. 5.8). At depths of 6.5 km (Fig. 5.9), large areas of the Canadian Cordillera and parts of the WCSB show temperatures of 150 to 200 °C. These represent the best target areas under the most likely limit of drilling depths, as based on drilling costs and technical abilities in the foreseeable future. However, drilling to depths of 10 km is potentially feasible in the future and these depths have already been achieved (e.g. the deep drilling project on the Kola Peninsula). At 10 km we can expect EGS temperatures (Chapter 8) in the 150 to 200 °C range across most of Canada (Fig. 5.10), except in some areas of the Canadian Shield. At this depth, temperatures in the 200 to 300 °C range are estimated for large regions of the Canadian Cordillera and the WCSB.

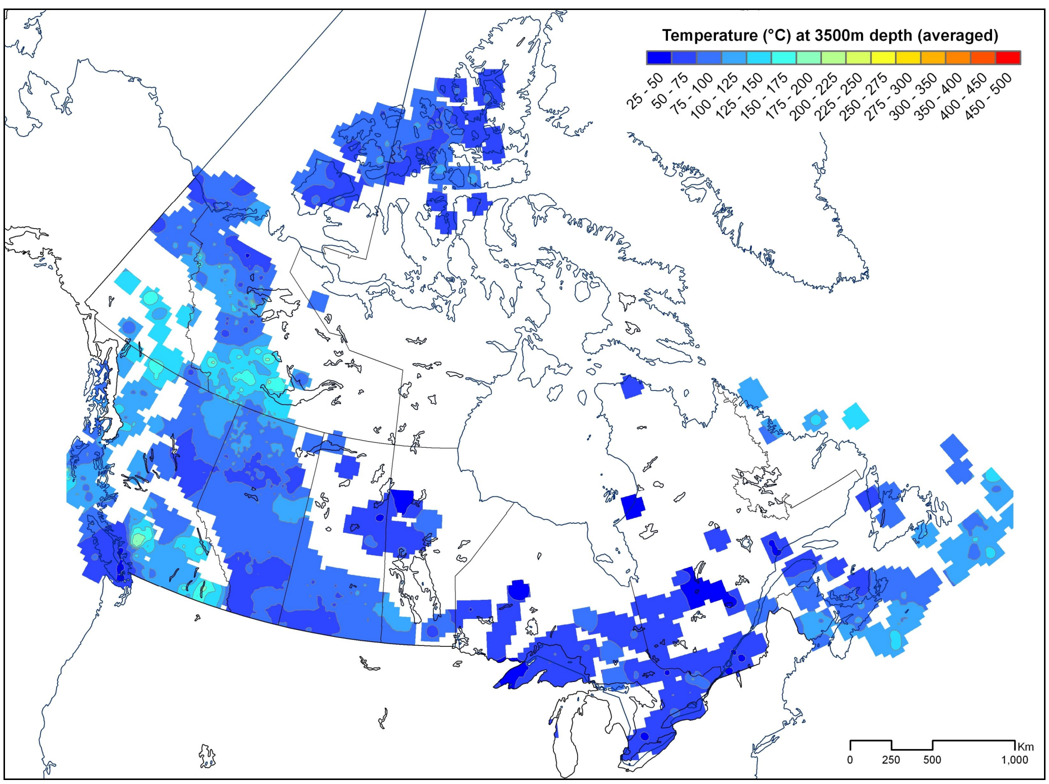


Figure 5.8. Temperature at 3.5 km depth.

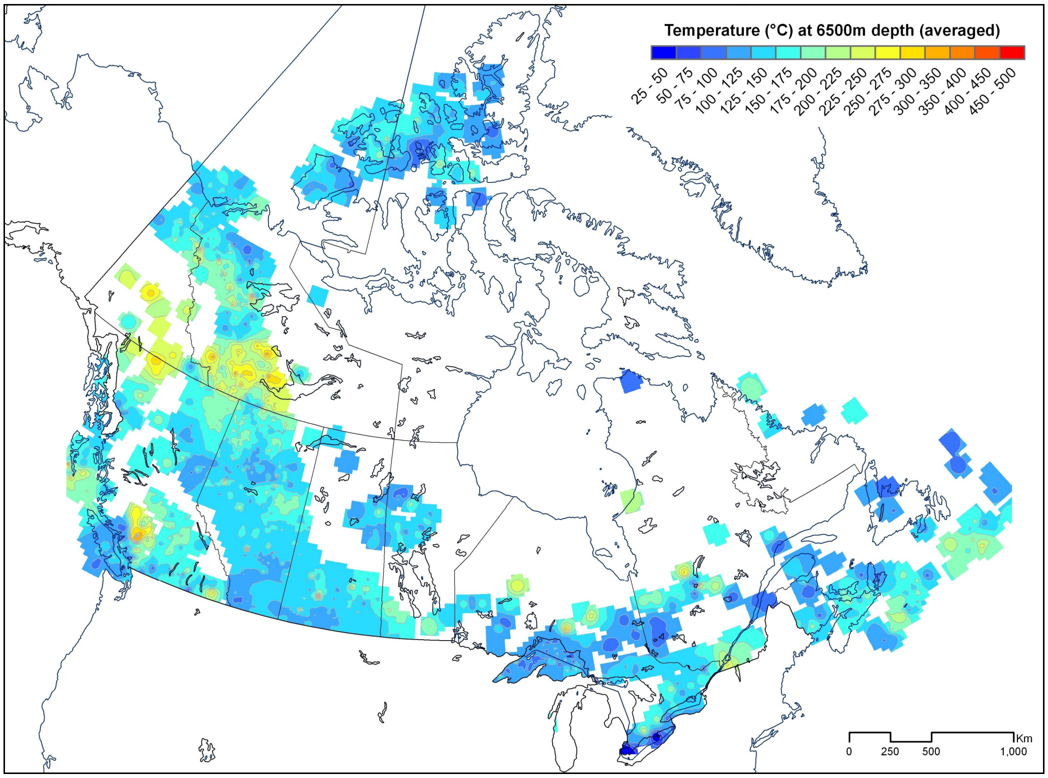


Figure 5.9. Temperature at 6.5 km depth.

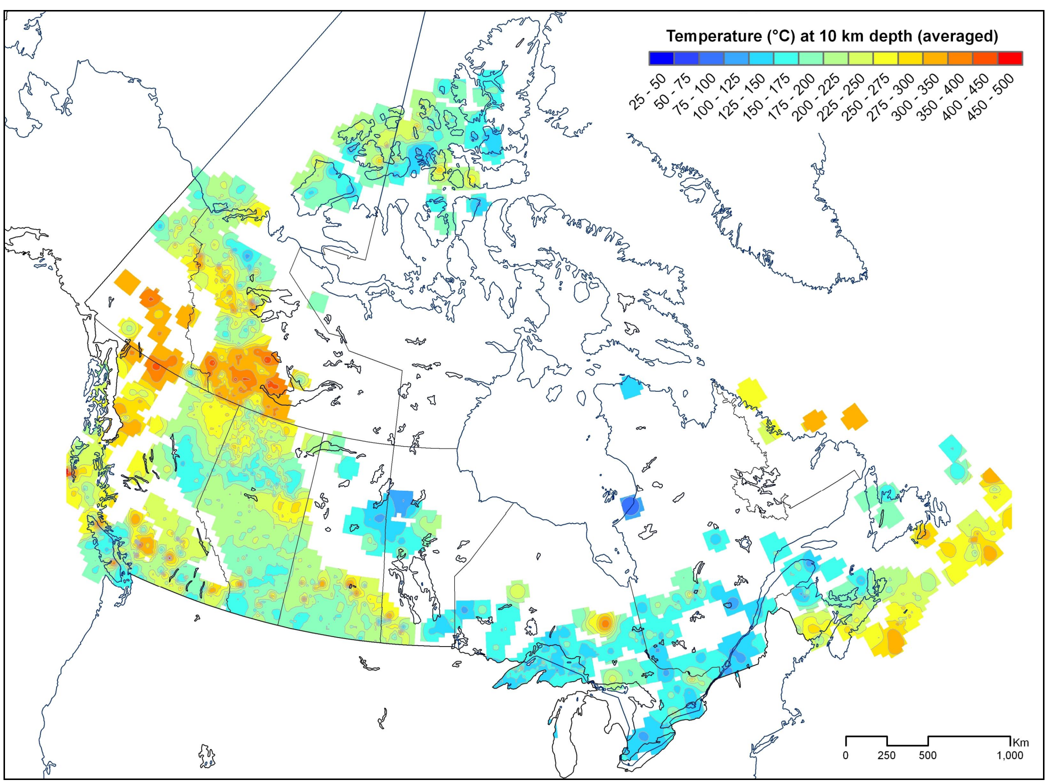


Figure 5.10. Temperature at 10 km depth.

5.5 DEPTH-TEMPERATURE MAPS – SHALLOW SYSTEMS

The evaluation of shallow geothermal energy potential, based on heat pump systems, requires precise temperature data and temperature contour maps depicting spatial variation in >0 °C temperatures at different depths. It also requires ground surface temperature distribution patterns. In this later case we need to estimate temperature based on temperature logs usually taken below the piezometric (groundwater level) surface (varies from metres to tens/hundreds of metres) and model it to the ground surface. The shallow (tens to hundreds of metres) thermal gradient is controlled by downward heat flux related to recent surface climatic forcing in the last few centuries (warming air temperature will cause near surface thermal gradients to be negative, and downward heat flow will heat the rock mass). The impact of near surface warming also needs to be taken into account when evaluating shallow (tens to hundreds metres) underground heat energy potential (Majorowicz et al., 2009).

Maps of temperature at depths 0, 50, 100, 150, 200, 250, and 300 m were constructed for all of Canada. The temperature data are based on the high precision well temperature logs (some with multiple temperature-depth logs) from boreholes/wells across Canada. The temperature data consists of point temperature vs. depth measurements in shallow boreholes that have reached thermal equilibrium conditions. Recordings of temperature are usually spaced between 2-10 m, from the top of the water level in the well to the well's bottom (measurement intervals vary from 2 m (minimum) to 20 m (maximum) depending on the individual temperature log's operator's preference). An example temperature-depth profile measured in a well at Winagami Provincial Park in Alberta (Majorowicz et al., 2006) is shown in Figure 5.11. Such temperature records were compiled from several existing data files and unpublished data across Canada.

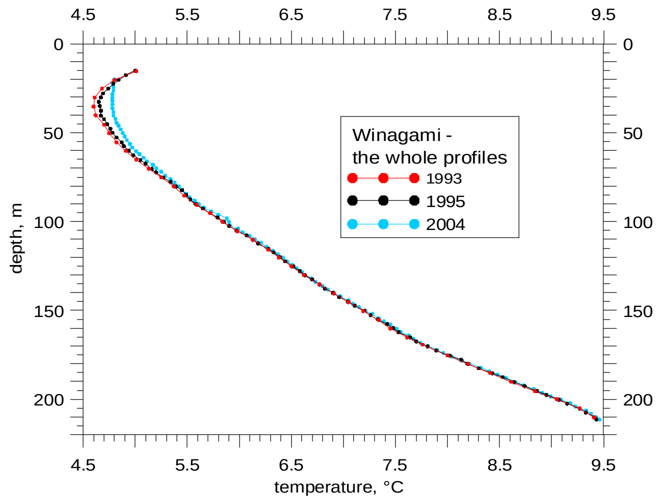


Figure 5.11. Example of temperature logs with depth (series of logs taken in a well at Winagami, Alberta). Source: Majorowicz et al., 2009.

Temperature – depth data sources include:

1. Temperature data measured north of 60 °N in Canada by Earth Physics Branch EMR (A. Taylor, A. Judge, M. Burgess and V. Allen) and published in a series "Canadian Geothermal Data Collection" – Geothermal Series, EMR Earth Physics, Branch between 1973 and 1981 AD (Earth Physics Branch EMR, 1974, 1975, 1976, 1977, 1979, 1981) as listings and graphic plots of temperature vs. depth.

2. Temperature logs across Canada (mainly eastern Canada and British Columbia data) from the database of the International Heat Flow Commission (IHFC) and NOAA Borehole Temperatures and Climate Reconstructions Database. These data were collated by the University of Michigan and were provided by several Canadian researchers and US researchers (WG) (A. Jessop, K. Wang, J-C Marschall, J. Majorowicz, W. Gosnold). Names of data providers, logging dates, locations and temperature – depth pairs are given in that data base: (http://www.geo.lsa.umich.edu/climate/NAM.html).

3. Unpublished logs done during a time period between 1991-2006 in Western Canadian Sedimentary basin by Northern Geothermal Consultants, Edmonton and EMR Earth Physics Branch and – GSC Calgary; these data are in the GSC Calgary Canadian temperature data collection; Jessop et al., 2005).

All of the data collected were from high precision temperature-depth logs taken by thermistor probes commonly calibrated to accuracy of 0.03 °C and attached to an electrical cable. In some cases, temperature data were recorded with a data logger, while in other cases, manual measurements were made. The probe is lowered in the borehole and temperature measurements are made at depth intervals in the part of the borehole filled with water. The boreholes logged were usually drilled for mineral prospecting and hydrogeology observational networks (Alberta and Saskatchewan). These boreholes are in thermal equilibrium attained years after initial drilling disturbance. Temperatures at 50, 100, 150, 200, 250 and 300 m were taken either, directly from temperature readings, or calculated from data points above and below using thermal gradient between the points. In some cases, a single site has multiple logs or logs taken at several boreholes at locations within 20-30 m radius (Alberta water observation wells). These data were averaged for the site.

Resultant maps are shown in Figures 5.12 to 5.17. These maps show two main general trends, as would be expected; a decrease in temperature northward and an increase in temperature with depth for any location. The >5 °C isoline, defining areas suitable for shallow geothermal energy use, can be reached by communities in southern Yukon and NWT when drilled to depth >100 m. At 250 m, temperatures as high as 10 °C can be reached in certain places. Southern Canada, where the highest temperatures are reached at shallow depths, is very promising for use of geo-exchange systems.

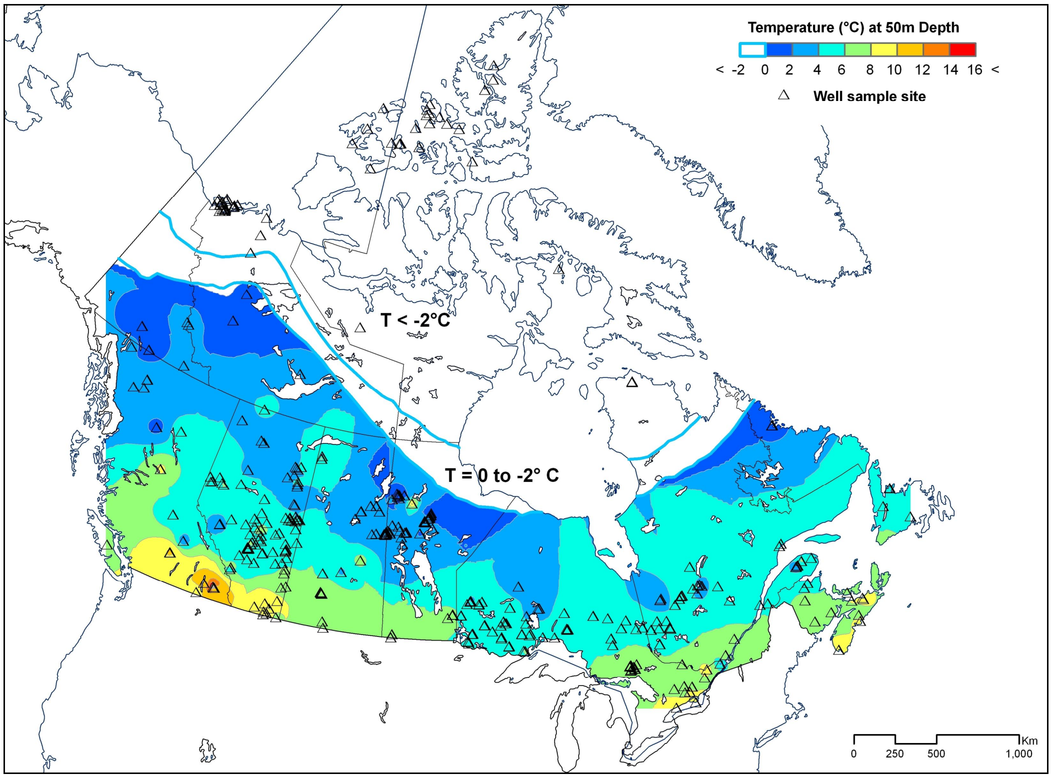


Figure 5.12. Temperature at 50 m depth.

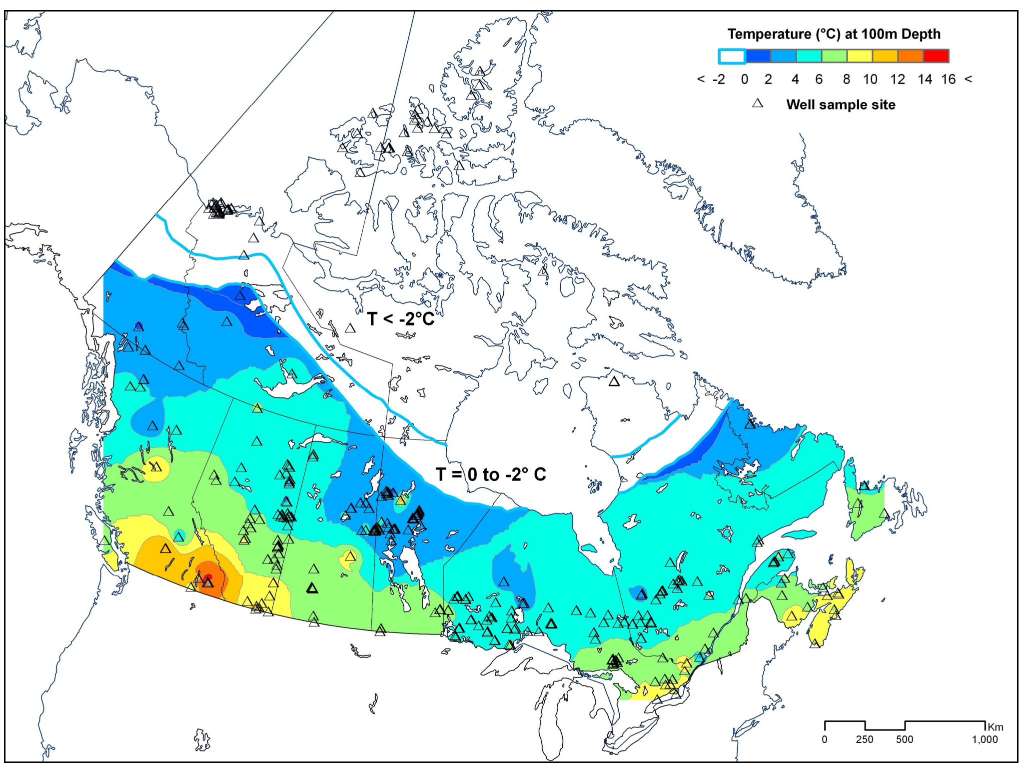


Figure 5.13. Temperature at 100 m depth.

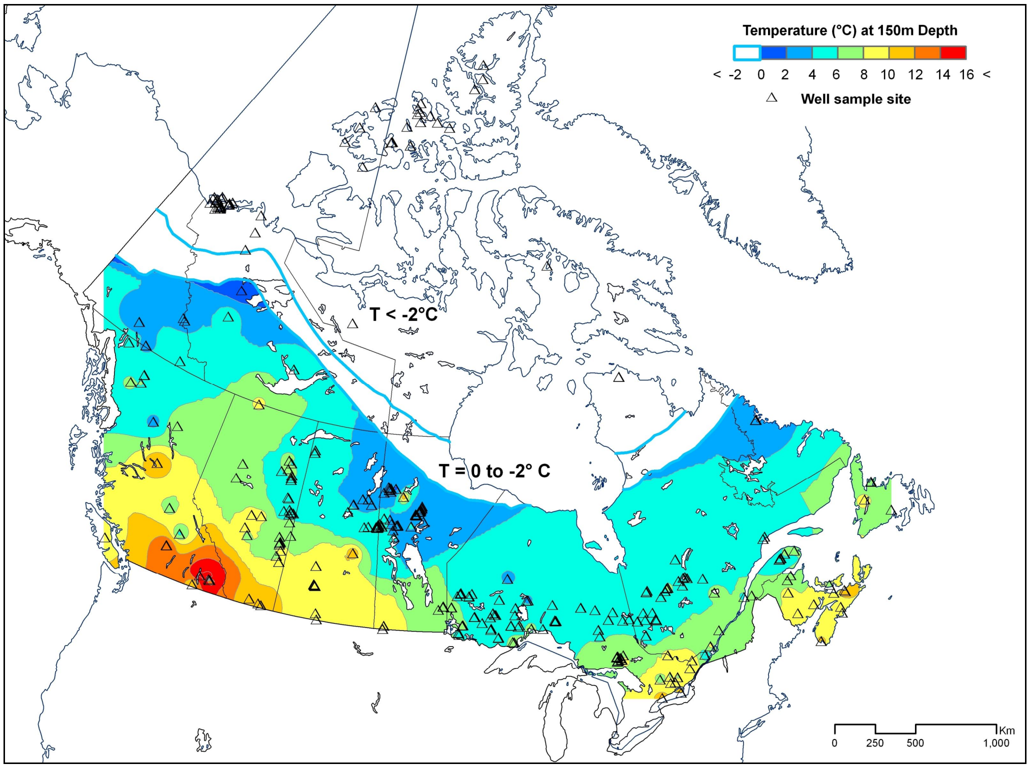


Figure 5.14. Temperature at 150 m depth.

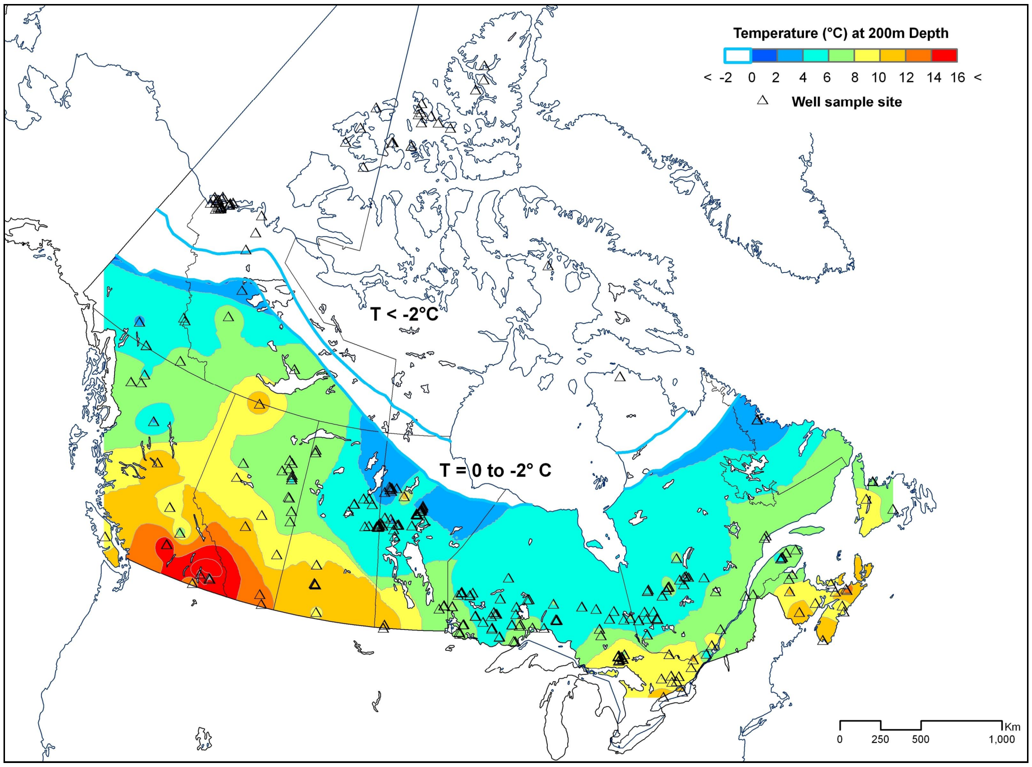


Figure 5.15. Temperature at 200 m depth.

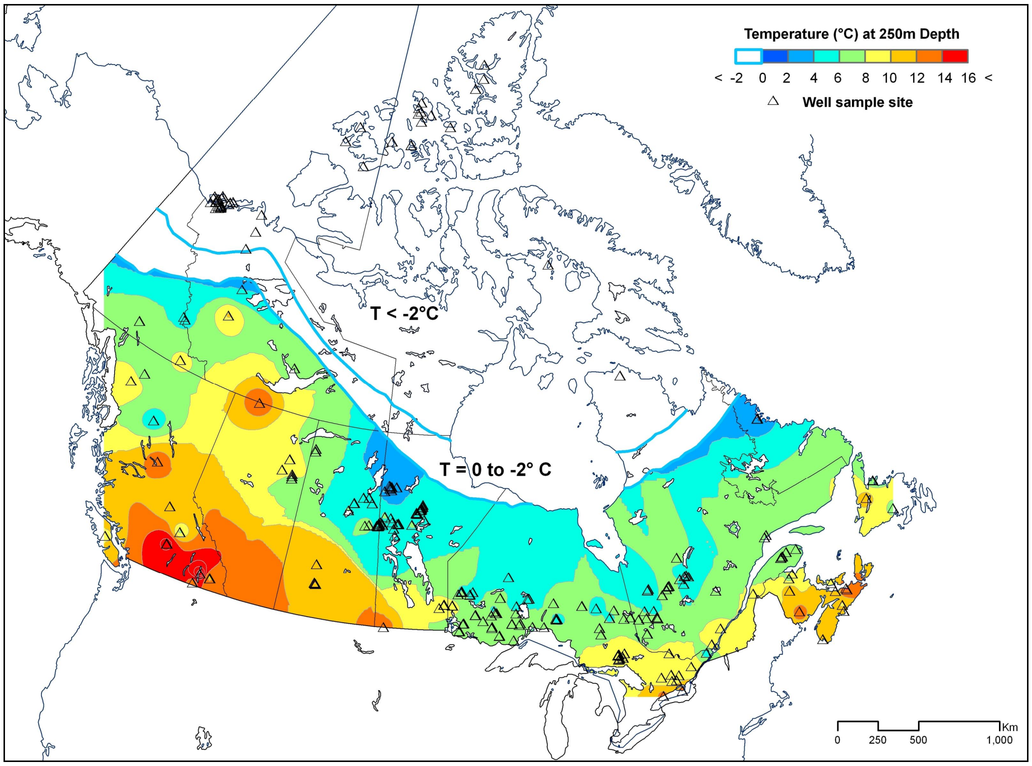


Figure 5.16. Temperature at 250 m depth.

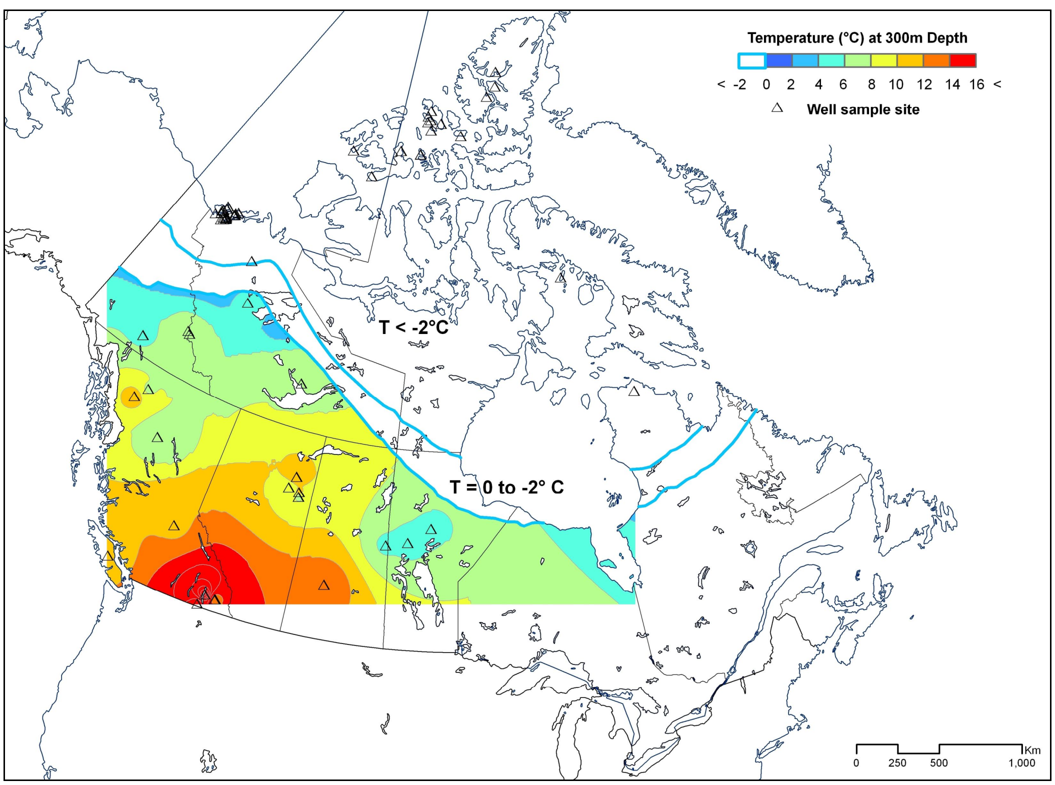


Figure 5.17. Temperature at 300 m depth.

5.6 GEOTHERMAL RESOURCES OF HEAT EXCHANGE SYSTEMS

Energy stored as underground heat can be calculated for specific depth slices of defined thickness and aerial extent. This provides a first order assessment of available geothermal energy. Here we calculate heat content in 1 km long x 1 km wide x 0.05 km thick slice, which is at an initial temperature of 1 to 10 °C as shown in Figure 5.12. Reasonable average values are 2,550 g/m^3 and 1,000 J/kg °C, for the density (ρ) and heat capacity (C) of rock are used. If this mass of rock is cooled through a temperature difference of δT °C (calculated here as a difference between ground temperature at 50 m depth and surface air temperature during the heating season) then the potential heat removed is given by:

$$Q=\rho C_p V \delta T \quad (5.6)$$

At first we calculate temperature difference between the 50 m depth temperature field and surface temperature (air temperature monthly normals), as shown for the example of Nain NL (Fig. 5.18). Figure 5.19 shows this result, and the spatial variability in net difference across Canada. This figure excludes temperatures less than 0 °C, where permafrost conditions occur (Smith and Burgess, 1998), which require drilling to depths greater than our evaluation of the shallow (50 m) resource.

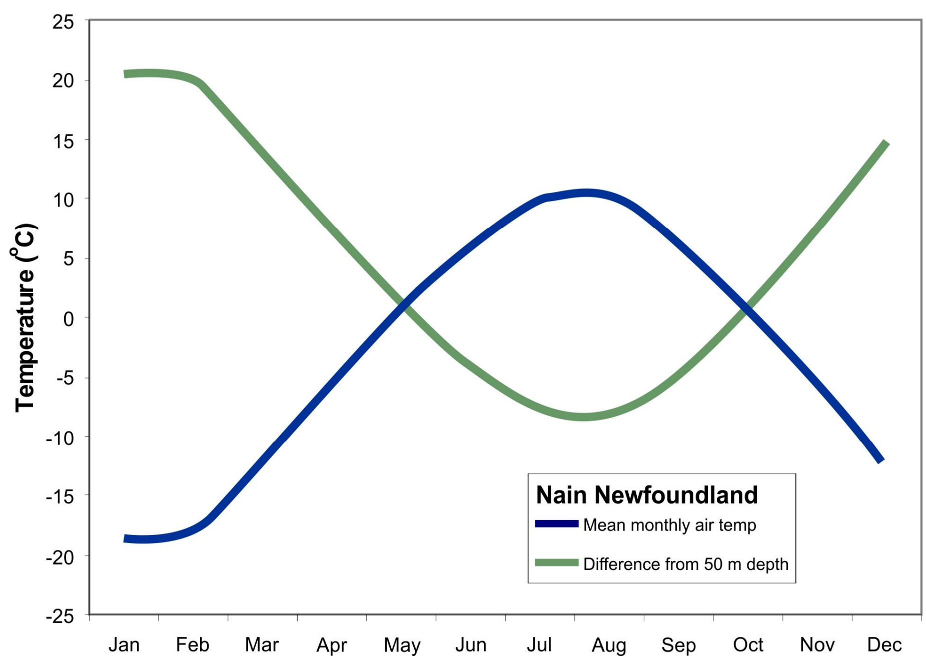


Figure 5.18. The difference between mean monthly temperature and soil temperature calculated to a reference depth of 50 m for the Nain meteorological station in NL. Source: Majorowicz et al. (2009).

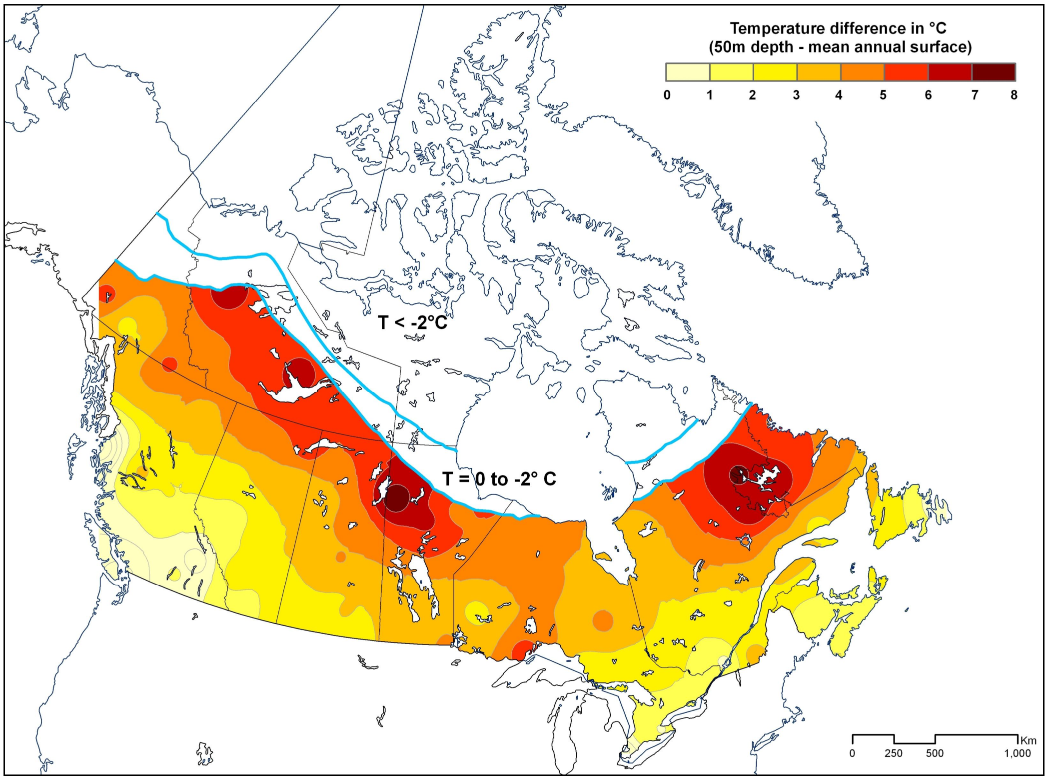


Figure 5.19. The temperature difference between air temperature mean (Canadian air temperature normals) and temperature at a reference depth of 50 m. The areas with temperature less than 0 °C are marked.

Most regions of Canada in the non-permafrost areas have ground temperatures at 50 m (well below depths of annual to decade change) as much as 7 ^{o}C higher than mean surface temperature measured at screen level of meteorological stations. This implies that large amounts of thermal energy are stored in the shallow geological environment. The quantity of thermal energy, which could potentially be released from 1 km^2 area block of 50 m of rock was also mapped for all of Canada in J (Joules) calculated per sq. km areas (Figs. 5.20-5.22) for the mean annual (Fig. 5.20), heating season (Fig. 5.21) and heat sink during cooling season (Fig. 5.22) for air conditioning of buildings, etc.. As deep temperatures are higher than surface air temperatures (Fig. 5.18), the net amount of energy is positive for most of Canada (Fig. 5.20) in the 1-10 x 10^{14} J/km^2 range and mainly 3-8 x 10^{14} J/km^2. Some areas like southern British Columbia and southern Ontario have lesser amounts of net annual energy balance available (0-3 x 10^{14} J/km^2). Northern areas, however, south of permafrost limit have the highest energy values (6-10 x 10^{14} J/km^2).

During the heating season, the amount of available energy for the block of 50 m and area of 1 km^2 is in millions (1-2) of Joules (10^6 J) for most of the Canadian territory south of the permafrost limit, with northern and central Canada having the highest values (Fig. 5.21). The conversion factors are such that 1J= 2.78 x 10^7 kWh. For example, the amount of energy available during the heating season is 2 x 10^6 J in the Winnipeg area; so we can have some 0.7 x10^{-1} kWh.

Energy savings on air conditioning are also available during the summer, especially in the high temperature regions of southern Ontario and the Prairies, where ground temperatures in the summer provide a heat sink (Fig. 5.22) which can be utilized with heat pumps for air conditioning. Of course, the size of the accessible resource is much smaller than implied by this simplistic analysis. This depends on the local engineering geothermal projects and the efficiency of the geothermal energy recovery.

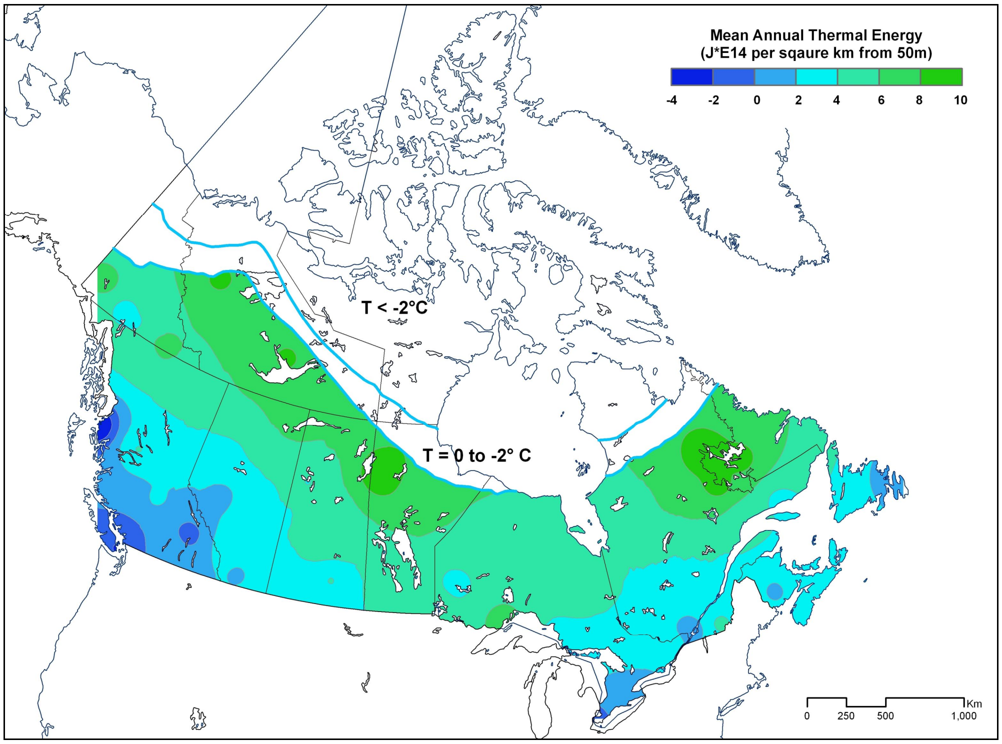


Figure 5.20. Mean annual thermal energy calculated for an average difference in temperature between reference 50 m depth and mean annual surface air temperature from Canadian normals.

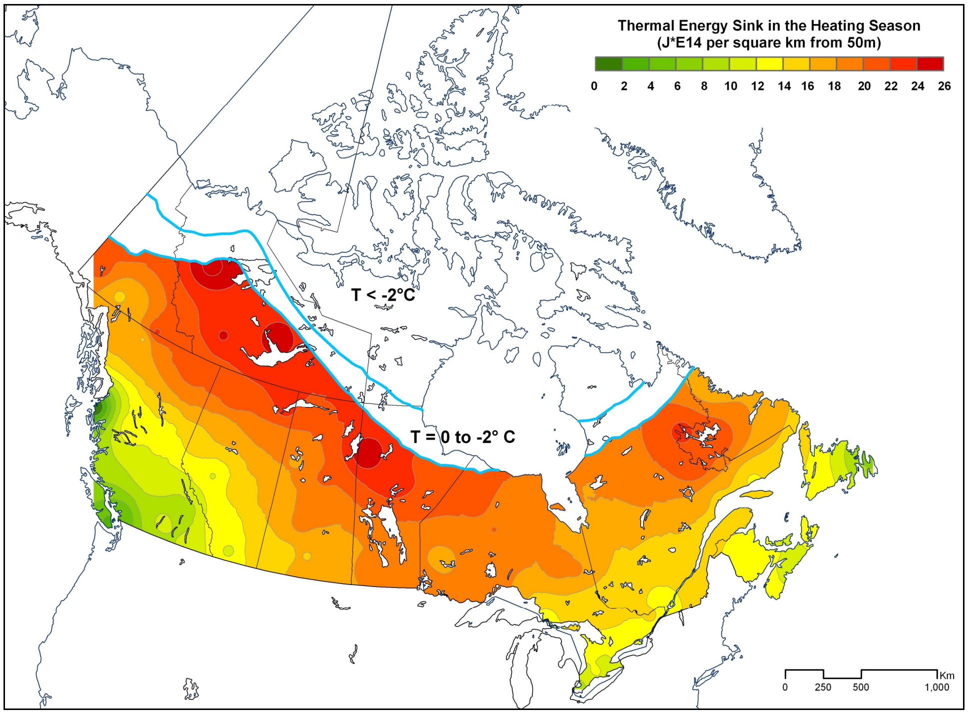


Figure 5.21. The thermal energy sink calculated for an average difference in temperature between reference 50 m depth and mean heating season surface air temperature from Canadian normals.

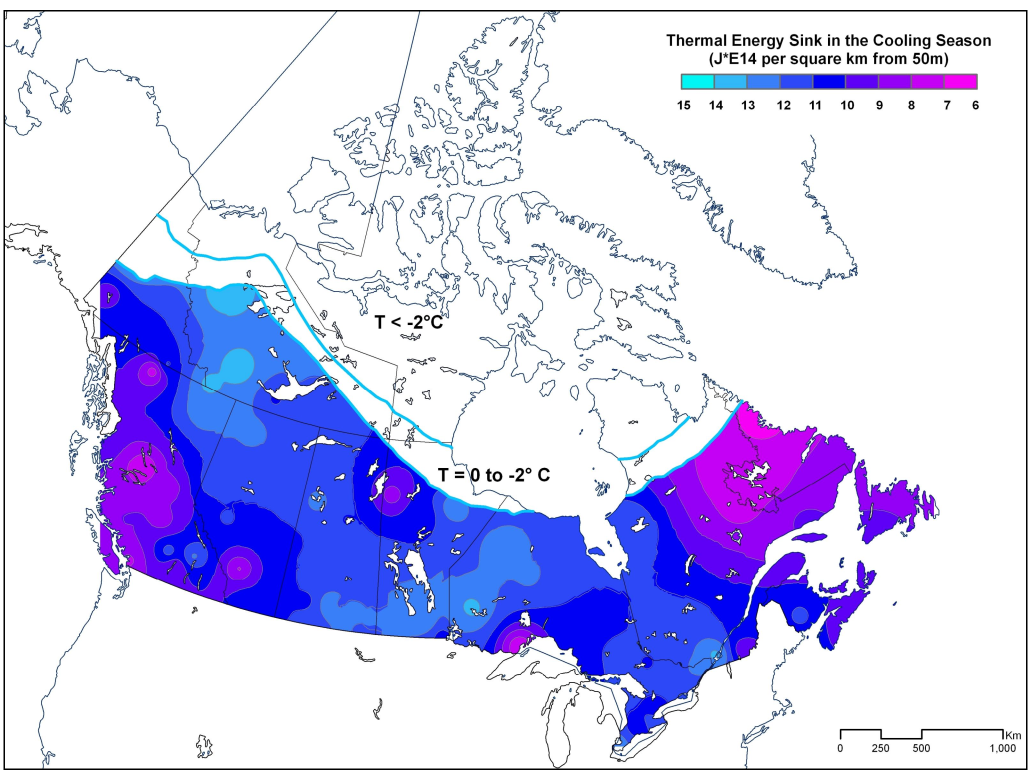


Figure 5.22. The 'cooling season' energy calculated for an average difference in temperature between reference 50 m depth and mean summer air temperature from Canadian normals.

6. GEOTHERMAL ENERGY AND MINES

6.1 INTRODUCTION

Mine sites can contain large volumes of groundwater, surface water, or mine waste materials, that can be used for space cooling and heating with ground source heat pump systems. The most commonly used resources are groundwater that can be pumped from and injected into high-permeability underground workings at a flooded mine to operate a heat pump system. In that case, the mine workings act as a heat exchanger, which reduces the number of wells that need to be drilled to install the system. The capital investment is therefore reduced compared to a conventional ground source heat pump system that may require drilling several hundred metres of borehole to install open or closed loop ground heat exchangers (Florides and Kalogirou, 2007). The payback period for the system installed at a mine site is consequently shorter, making it attractive because of energy savings and reduced greenhouse gases emissions when compared to other conventional heating and cooling alternatives. Additional resources of mine sites, such as surface water and waste materials, which are discussed in this chapter, can advantageously be used with ground source heat pumps systems in various configurations.

The first heat pump system reported to operate from an abandoned mine was installed in 1989 in Springhill, Nova Scotia, where groundwater is pumped from coal mines (Jessop et al., 1995). Similar systems have been operated within lead mines at Park Hills in the US (Geothermal Heat Pump Consortium, 1997), and within coal mines in Shettleston and Lumphinnans in the UK (Watzlaf and Ackman, 2006) and in Heerlen in The Netherlands (Bazargan Sabet et al., 2008). The geothermal potential of other flooded underground mines has recently been assessed in Canada (Ghomshei and Meech, 2003; Ghomshei, 2007; Raymond and Therrien, 2008), Europe (Malolepszy et al., 2005; Tóth and Bobok, 2007; Wieber and Pohl, 2008; Rodríguez and Díaz, 2009; Hamm and Bazargan Sabet, 2010) and the US (Watzlaf and Ackman, 2006). The geothermal resources studied at mine sites are, however, not limited to flooded underground mines. For example, ground source heat pump systems are being used with surface water from a flooded open pit quarry at Saint-Bruno-De-Montarville in Québec (Raymond et al., 2008). In another study, Raymond (2010) assessed the potential of geothermal energy exchange using closed-loop ground heat exchangers at the South Waste Rock Dump of the Doyon Mine in Québec.

Canada has a long mining history and, therefore, hosts abundant geothermal resources located at mine sites. The exploitation of mineral deposits across the country began more than one century ago (Udd, 2000). Mining operations during the early and mid 1900's were typically located close to communities, which can now benefit from the exploitation of geothermal resources using heat pumps as this technology is best exploited within a few kilometres from the bore field. Energy saved for space heating and cooling can help industries stay competitive, while contributing to the reduction of greenhouse gases emissions. This chapter contains a description of geothermal resources associated with base metal, industrial mineral, and coal mines in Canada followed by a review of recent projects. An inventory of abandoned mines in British Columbia, Alberta, Saskatchewan, Québec and Nova Scotia is then presented to provide an estimate of the geothermal resources associated with mine sites and highlight their potential for energy exchange.

6.2 GEOTHERMAL RESOURCES IN MINING ENVIRONMENTS

6.2.1 Resource Features

Mining environments host low-temperature geothermal resources that originate from the Earth's natural heat flux (Chapter 1), but are improved due to mining activities. For example, a network of underground workings increases the global permeability of the subsurface, which can in turn allow pumping groundwater at high rates. This increase in permeability is valuable because geothermal heat pumps require high operating flow rates that are about 3.3×10^{-5} to 6.7×10^{-5} m^3/s (2 to 4 L/min) for each kilowatt of heating or cooling capacity. For large operations, like a district system, theses flow rates can only be obtained from highly permeable aquifers or with the installation of hundreds of metres of closed-loop ground heat exchangers.

Another characteristic of mining environments is the increased subsurface temperatures caused by mineral oxidation, with pyrite oxidation being the most common. Pyrite (FeS_2) is commonly found in waste and host rock of base-metal mines and it reacts with water and oxygen in a strong exothermic (heat generating) reaction given by:

$$FeS_2 + 3.5O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ + 1409\ \text{kJ} \qquad (6.1)$$

This compact form of the reaction does not entail all the complex mechanisms involved in pyrite oxidation (Lowson, 1982; Ritchie, 1994) but indicates that, for each kilogram of oxygen consumed, the amount of energy released is about 12.6 MJ. Heat produced by the reaction is transferred to the subsurface, where the temperature can build-up. Heat transfer occurs by conduction through rocks or by convection if there is groundwater flow in the pore spaces of waste and host rock materials. For example, temperatures higher than 40 °C have been measured in the South Waste Rock Dump of the Doyon Mine, Québec, more than 20 years after the waste dump was constructed (Raymond et al., 2008). At the Britannia Mine in British Columbia, water infiltrates the mine upper workings and discharges at a lower level at a temperature of 15 °C, which is about 3 °C warmer than the temperature of the shallow subsurface in the area (Ghomshei and Meech, 2003).

The reaction shown in Equation 6.1 is, on the other hand, responsible for the production of acid mine drainage. Water in mining environments that undergo mineral oxidation can be of various chemical compositions (Banks et al., 1997). Ground source heat pumps used under acid conditions can be protected by selecting appropriate system configuration and materials. Intermediate plate heat exchangers, used with open-loop systems fed by groundwater and surface water, eliminate the circulation of water directly into the exchangers of the heat pump (Rafferty, 2003). Thermal energy is transferred by conduction between a mixture of water and antifreeze that flows in the heat pump and the external water taken form the earth side of the system, without exchange of fluids at the intermediate plate exchanger. This configuration reduces the risk of damaging the heat pump unit and facilitates maintenance because intermediate plate heat exchangers are made of corrosion resistant materials, such as stainless-steel, and they can be easily dismantled. Alternatively, high-density polyethylene piping is commonly used with closed-loop heat exchangers, either installed in surface water bodies or buried underground, and is resistant to various chemicals including sulphuric acid (Budinski and Budinski, 2005). The design of a system can therefore be adapted to a specific mine site.

6.2.2 Resource Types

There are three types of geothermal resources associated with base-metal, industrial mineral, and coal mines according to the different geoexchange technologies presented in Chapter 2. The resource types are aquifers, surface water bodies and mine waste. For each geothermal resource type, a specific ground source heat pump is used to extract or inject heat. Groundwater, surface water and ground-coupled heat pumps (ASHRAE, 2007) are discussed in this chapter to describe the various systems associated with each geothermal resource type.

The first resource type, aquifers, can be exploited with groundwater heat pumps having an open loop configuration. Methodologies have recently been developed to assess the geothermal potential of an aquifer that floods abandoned underground mines, both with analytical (Rodríguez and Díaz, 2009) and numerical models (Renz et al., 2009). Analytical models are appropriate to compute heat exchange rates for a given underground section of a mine, such as a shaft, a road or a tunnel, whereas numerical models can assess the site's global potential by accounting for the complex geometry of the underground workings. Water that is already pumped at active mines to keep excavations dry can also be used with groundwater heat pumps, but few studies have been conducted to assess that potential. At the Mouska Mine in Québec, a mid-size gold operation covering 876 hectares with shafts down to a depth of 560 m, the mine workings are dewatered at an average rate of 2.25×10^{-2} m^3/s (1 350 L/min). Design calculations indicated that a heat pump system could use this water to heat buildings with a maximum peak load of 870 kW, assuming a production temperature of 10.1 °C (Raymond et al., 2010b).

The second resource type is surface water bodies such as ponds or flooded open pits, which are common at mine sites. Heat can be extracted from these water bodies using surface water heat pumps with an open or a closed loop configuration. Water is directly taken from the surface water body in the open loop configuration. Coils that are sunk into the surface water body allow heat exchange within a closed loop configuration. Shallow ponds, which are typically found at active mines, store water of various chemical compositions and they can remain on site after mine closure. Flooded open pits, most commonly encountered at closed mine sites, can be deep and offer significant geothermal potential, which mainly depends on the water volume, inflow, outflow and temperature (Hattemer and Kavanaugh, 2005). The main advantage related to surface water heat pumps on mine sites is that the surface water bodies are generally located on private lands, where regulations associated with the installation can be less restrictive. Heat pumps that use surface mine water are in operation near the Goyer Quarry, in Saint-Bruno-De-Montarville, Québec (Figure 6.1). The quarry contains 8,064,000 m^3 of water that feeds the heat pumps of condominium complexes, each covering a total area of 6,039 m^2 and containing 36 apartments (Raymond et al., 2008). Two complexes were present on site in 2011 and additional construction is planned by the real estate developer. Thermal energy from the surface water pumped in the quarry is exchanged with a shared plate heat exchanger linked to the heat pumps that all have a combined capacity of 3.6 to 5.6 kW and which are located in the apartments.

Figure 6.1. Images of the Goyer Quarry in Saint-Bruno-De Montarville, its condominium complex that uses surface water heat pumps, and the shared intermediate plate heat exchanger located in the building basement.

The third resource type, mine waste, was proposed to be the host for ground-coupled heat pumps (Raymond et al., 2010b). Buried pipes with a closed loop configuration in horizontal trenches or vertical boreholes typically make the ground heat exchangers for these systems. Large operations require several exchangers that are sized to maintain a minimum or maximum outlet temperature during peak conditions (Bernier, 2000). Enhanced temperatures associated with mine waste rock can therefore be used to reduce the length of the exchangers required for a given system designed according to heating loads. This setting is advantageous because shallow subsurface temperatures in Canada rarely exceed 10 °C (Section 5.5). Numerical modelling of a system installed under the South Waste Rock Dump of the Doyon Mine has shown that operating temperatures of heat exchangers can be maintained during the life of a heat pump, but further demonstration of the benefits of this technology is necessary (Raymond, 2010).

6.2.3 Resource Evaluation

The geothermal energy resources that can be extracted from a medium can be evaluated from its volume, volumetric heat capacity and temperature, as well as the temperature to which it can be lowered to, using Equation 5.6 presented in Chapter 5. The difference between the temperature of the medium and the return temperature is estimated from the difference between the subsurface temperature and the mean atmospheric temperature at a given location. This temperature difference, however, is arbitrary for heat pumps because systems can return water below the mean atmospheric temperature. The potential for an underground heat sink using heat pumps is similarly estimated with a temperature differential that is reversed since the return temperature is warmer than the subsurface temperature. The volume of the medium, which is mine water or waste in the case of mining environments, can be estimated from two approaches using mine production records or archived maps. Mine water hosted in underground workings is used, for example, to estimate the medium volume since most projects that are further described concern flooded underground mines. The calculation does not account for water contained in the pores of the surrounding host rock.

The first approach consists of converting the mass of ore mined into the volume of voids, that are assumed to be flooded, by dividing tonnage records by the rock density and then multiplying by a correction factor of 0.25 (Jessop et al., 1995) to account for subsidence and backfill. The correction factor is a conservative estimate of the voids that can remain after mine closure. Representative rock densities of 2,700 kg/m and 1,500 kg/m can be used for base-metal and coal mines, respectively. Appropriate transformation of units must be applied to convert tons in kilograms. In many cases, mine records or inventory data do not mention if tons are metric or imperial. Thus, metric tons are assumed for calculation knowing that it can yield a 10% uncertainty. In the second approach, the water volume flooding a mine is estimated by multiplying the sum of the areas covered by underground workings by the average thickness of the workings and, again, by a correction factor of 0.25 to account for subsidence and backfill. Resource calculations using this method are presented below for the Springhill project and the inventory of resources in Canadian provinces.

6.3 RECENT CANADIAN PROJECTS

Most geothermal studies conducted at mine sites in Canada evaluated the potential of flooded underground mines. Results from the system operated at Springhill, presented in Chapter 4 as part of the National Geothermal Energy Program, and from feasibility studies carried out at the Britannia and the Gaspé Mines are reviewed below. An additional project from the South Waste Rock Dump of the Doyon mine is presented.

6.3.1 Geothermal Operation from Springhill's Coal Mine, Nova Scotia

In 1985, the Earth Physics Branch of the Federal Department of Energy, Mines and Resources, which became the Geological Survey of Canada, conducted a feasibility study to evaluate the geothermal heating potential of the abandoned underground coal mine in Springhill (Figure 6.2) that closed in 1958 (Jessop et al., 1995). Up to 22,337 tons of coal were mined from 7 coal seams dipping at 24 to 30° and down to a depth of 1,350 m. Geothermal operations from that coal mine represent one of the first major geothermal energy projects completed in Canada.

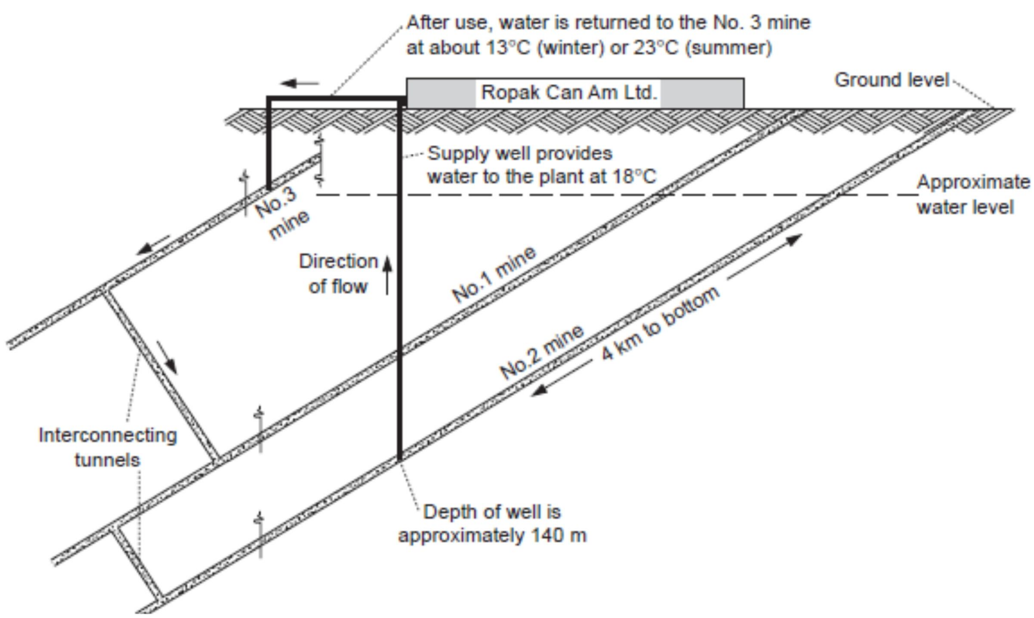


Figure 6.2. Vertical cross-section illustrating the groundwater heat pump system developed at the Springhill coal mine, Nova-Scotia (CADDET energy efficiency, 1992).

Energy resources contained in the water flooding the mine in Springhill were evaluated with Equation 5.6 using a water density and specific heat capacity equal to 1,000 kg/m and 4,200 J/kg/K, respectively. The temperature difference was initially assumed equal to 15 K, based on measured water temperatures near surface, which reached 20 °C, and assuming that the temperature of the water returned to the mine is 5°C. These numbers are slightly above the expected operating temperatures because all the heat available is computed for a resource estimate and only part of that heat may be used during operation of a heat pump. The water temperature of 20 °C measured near surface is higher than the shallow subsurface temperature at the Springhill coal mine. This increase was assumed to result from free and forced convection that transfers heat from the deeper sections of the mine to the surface. The volume of water flooding the mine was estimated with the two approaches given above, based on a mass of ore removed equal to 22,337 tons and a surface area covered by the coal seams equal to 4.19×10^5 m^2, assuming an average seam thickness of 10 m. The average obtained from the results of both approaches indicated a water volume of about 4.0×10^6 m^3 and the resulting geothermal energy resources were estimated equal to 250 TJ. This amount of energy represents the total heat accessible with heat pumps and does not account for heat that can be transferred to the mine water from convection of groundwater and heat exchange by conduction with the host rock.

Exploitation of geothermal energy resources began in 1989 to heat and cool the facilities of the Ropack Can-Am plastic transformation factory covering 13,500 m^2 (CADDET energy efficiency, 1992). Two wells were drilled to intercept the mine workings and pump the groundwater. Water pumped from seam no.2, located at an approximate depth of 140 m, had a temperature near 18 °C and water was returned to seam no.3 at a temperature of about 13 to 23 °C (Figure 6.2) during the heating and cooling season, respectively. Heat pumps therefore use only a part of the entire energy resources available from the mine water. Annually, more energy is returned underground than extracted because of heat gains due to work activities and operation of machinery inside the building. However, the temperature of the pumped water remains constant throughout the year, suggesting that the mine provides an efficient sink to the additional heat returned underground and that the cooling potential is preserved. Net energy savings for Ropack Can-Am during the first year of operation were about 600 MWh, which represented $45 000 in 1989. The capital cost of the heat pump system at that time was $110 000, yielding a payback period of less than 2.5 years.

Following the successful geoexchange operation at the Ropack Can-Am factory, other buildings were equipped with a groundwater heat pump system that taps the mine water at Springhill. A Pizza Delight restaurant was built in 1990 above the location of a coal seam whose depth reaches 1,063 m and the restaurant was equipped with a heat pump. Similar operations of groundwater heat pumps from M.B.B. Mechanical, a boilermaker, and Surette Battery, a battery manufacturer, were also reported. Annual energy savings during early operation for these buildings were between 40 and 45 % (Arkay, 1992). The proximity of the underground workings to the community of Springhill (Figure 6.3) was an asset to exploit the geothermal resources of the mine. With the deployment of several systems, Springhill pioneered large-scale exploitation of low-temperature geothermal resources in mining environments in Canada.

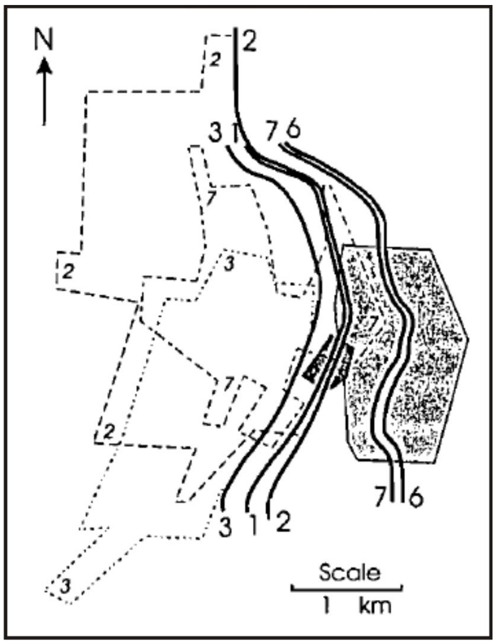


Figure 6.3. Map showing the position of coal seams (dash lines) and outcrops (continuous lines) relative to the town of Springhill (shaded areas; Jessop et al., 1995).

6.3.2 Feasibility Study at Britannia Mine, British Columbia

An underground copper mine abandoned in 1974 is located in British Columbia near Britannia Beach, a community of 250 people on the shore of Howe Sound, a bay north of Vancouver that connects to the Strait of Georgia. A mine was exploited in the surrounding mountains, with tunnels below the sea level (Figure 6.4). At the time of the study, groundwater that infiltrates the closed mine now discharged at

Howe Sound from the 4100 level of the mine and was an important source of acid effluents. Studies were conducted by Ghomshei and Meech (2003) to assess the geothermal potential of the groundwater discharging from the mine and which could be captured at a water treatment plant to mitigate the environmental impact of acid drainage. While the treatment plant is now in operation, the geothermal project has not been realized. Nevertheless, this example illustrates benefits of using mine water.

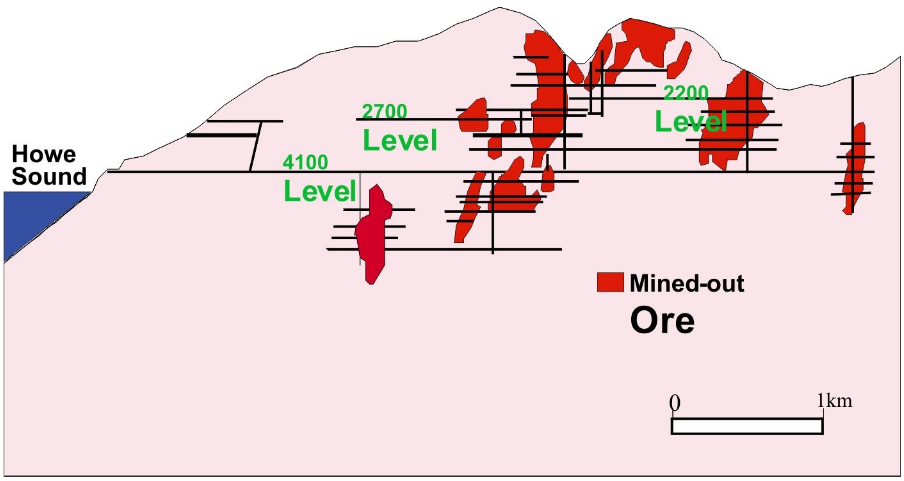


Figure 6.4. Vertical cross-section of the Britannia Mine (Ghomshei and Meech, 2003). Levels in feet indicate approximate mine depth.

The mine workings cover an area approximately equal to 2.0×10^{7} m^{2}, which was estimated in this project from the volume of mine tailings. The rate of heat that can be captured from the Earth's natural heat flux is estimated at about 1.3 MW by multiplying the heat flux (locally 65 mW/m) by the surface area of the workings. Heat released by pyrite oxidation and carried by groundwater is estimated at 2,386 KJ/m based on the metal content of water, which can be related to the production of acid mine drainage. Heat released by pyrite oxidation that can be captured during average conditions, considering groundwater discharge from the 4100 level of the mine at a rate of 0.167 m^{3}/s (1.0×10^{4} L/min), is therefore equal to 400 kW. The temperature of the discharging water is 15 °C, and because water flows freely out of the mine, pumping or drilling is not required. The costs of the installation can then be reduced compared to a regular ground source heat pump system. Geothermal operations were planned according to the conceptual system configuration illustrated in Figure 6.5, where geothermal energy is extracted at an intermediate plate heat exchanger linked to a heat pump plant networked to the community. The installation of intermediate plate heat exchangers is suggested to protect the heat exchangers of the heat pump, typically made of copper or cupronickel, because the mine water has a pH near 4 to 4.5 and can corrode metals.

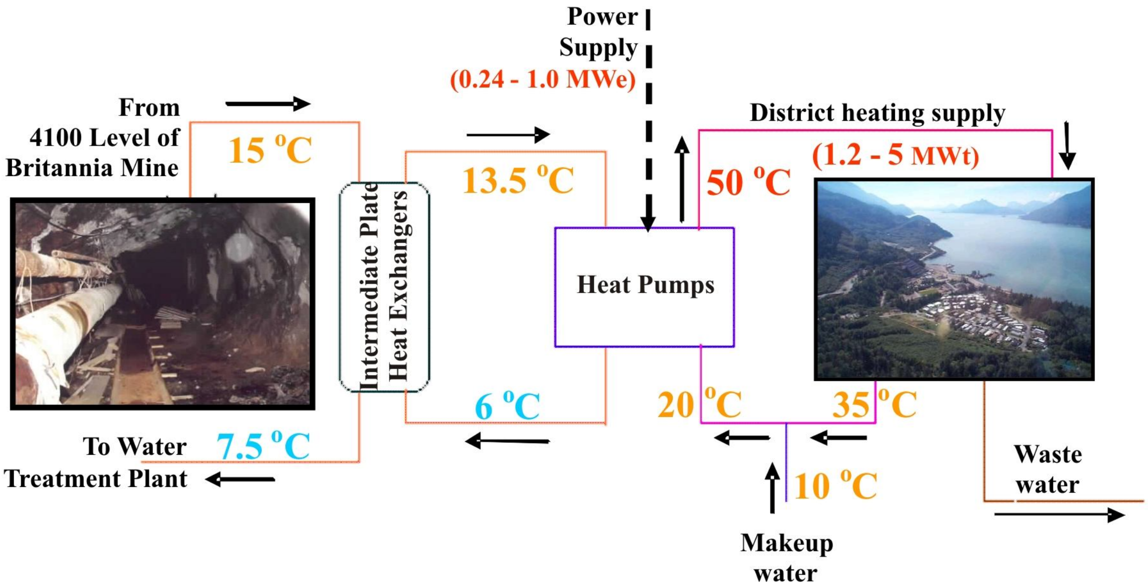


Figure 6.5. The groundwater heat pump system proposed at the Britannia Mine (Ghomshei and Meech, 2003).

With the proposed system, the total power available for heating can vary from 1.2 to 5.0 MW depending on the system operating flow rate that can be managed with water storage in the mine. The planned energy extraction rate may exceed the heat captured from the Earth's heat flux and the oxidation of pyrite, because exploited groundwater is returned to surface water bodies. The electric power consumed to operate the system is only 0.24 to 1.0 MW. The capital investment to install a district system with a power of 2.5 to 4 MW linked to the community was estimated between $2.0 and 2.5 M. Energy savings of $25 to 35 K per year were anticipated, with a payback period of 5 to 8 years. A water treatment plant was built in 2005 to mitigate acid drainage. The proposed groundwater heat pump system can still be incorporated to that plant.

6.3.3 Feasibility Study at the Gaspé Mines, Québec

Field characterization and numerical modelling studies were carried out to assess the geothermal heating and cooling potential of a district system at the flooded Gaspé Mines (Figure 6.6). The mine site is located in the middle of the Gaspé Peninsula in Québec next to the town of Murdochville, whose population is about 850. Copper porphyry and skarn mineral deposits were exploited from two open pits and a large network of underground workings. Mining operations conducted underground stopped in 1999 after removal of about 47 million tons of rock. Today, the flooded workings contain more than 3.7×10^6 m^3 of water and 61 TJ of geothermal energy. The town of Murdochville is planning a geothermal district system at its industrial park located directly above the mine workings. Installation costs and annual energy savings were estimated in 2006 at \$523 K and \$144 K, respectively. The town received funding in 2008 from the Green Municipal Fund and the *Ministère des Affaires municipals, des Régions et de l'Occupation du territoire* in Québec to cover installation costs. The municipal authorities are now looking for industrial interest to exploit the geothermal resources to construct the district system and benefit from the energy savings provided by the system operation. This incentive, along with others that involve retrocession of mine buildings to industries wishing to develop activities at the industrial park, are expected to stimulate the town's economy, which was negatively impacted after the mine's closure.

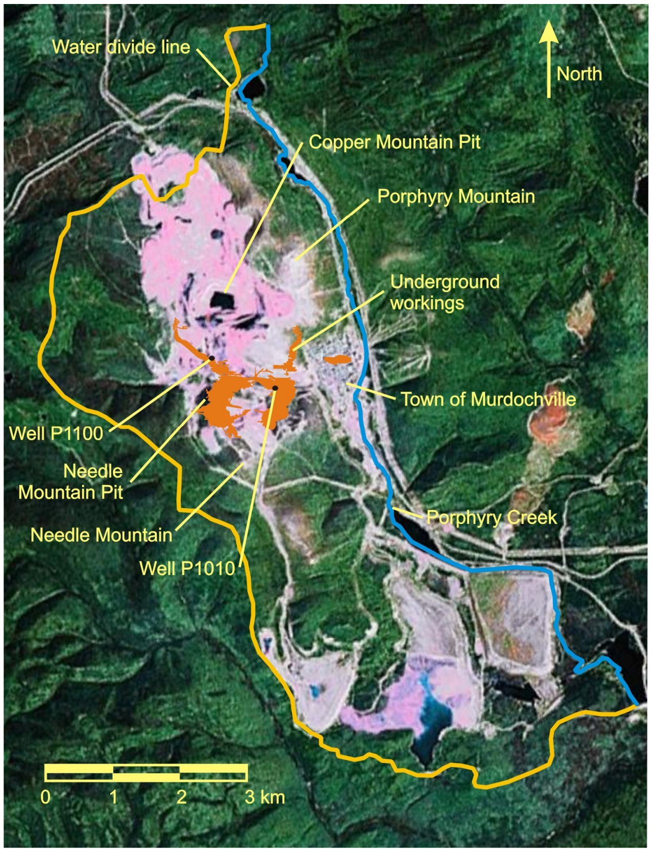


Figure 6.6. Satellite image showing the surface area covered by the underground mine workings of the Gaspé Mines (Raymond, 2010). Source for the background image: earth.google.com.

A pumping test was initially performed in the former mining shaft P1100 to determine the global hydraulic conductivity of the mine workings (Raymond and Therrien, 2008). Groundwater was pumped at 0.062 m^3/s (3 720 L/min) over 3 weeks and the average temperature of the water pumped was 6.7 °C. The analysis of the variations in hydraulic head at the mining shaft and in surrounding observation wells indicated that the hydraulic conductivity of the mine workings is approximately 1×10^{-2} to 1×10^{-3} m/s. A groundwater heat pump system was then simulated with a groundwater flow and heat transport model to optimize operation scenarios and to ensure a sustainable exploitation of the geothermal resources (Raymond, 2010). Numerical modelling of heat exchange in the underground mine is a challenging task because of the complex geometry of the workings, but appears to be the most appropriate method to predict the system behavior. The numerical modelling study conducted at the Gaspé Mines can be used as a guide for investigation of other sites and is outlined in this Chapter.

The numerical model of the Gaspé Mines, developed with the finite element simulator HydroGeoSphere (Therrien et al., 2010), contains 81,200 three-dimensional elements that are refined over the mine workings (Figure 6.7a). The horizontal extent of the domain covers the western part of the Porphyry Creek Watershed (Figure 6.7b). The host rock, the underground workings and the Copper Mountain Pit were discretized with 3D elements and 1D elements representing the mining shafts and the underground roads superimposed onto the 3D elements (Figure 6.7c). Variably-saturated groundwater flow and conductive-convective-dispersive heat transfer were simulated to reproduce the operation of the proposed district heating and cooling system, for which water is pumped and injected from the former mining shafts P1100 and P1010, respectively. The temperature of the water that is injected underground was computed with a heat pump function that accounts for the system coefficient of performance, which varies with temperature. The initial hydraulic heads specified for the simulation (Figure 6.7d) accounted for drawdown that occurred when the mine site was dewatered. The initial subsurface temperature (Figure 6.7e) was determined from the local geothermal gradient, which was measured and is about 0.0011 °C/m. The model was calibrated by reproducing both the groundwater level rebound following the mine closure and the pumping test conducted to characterize the site.

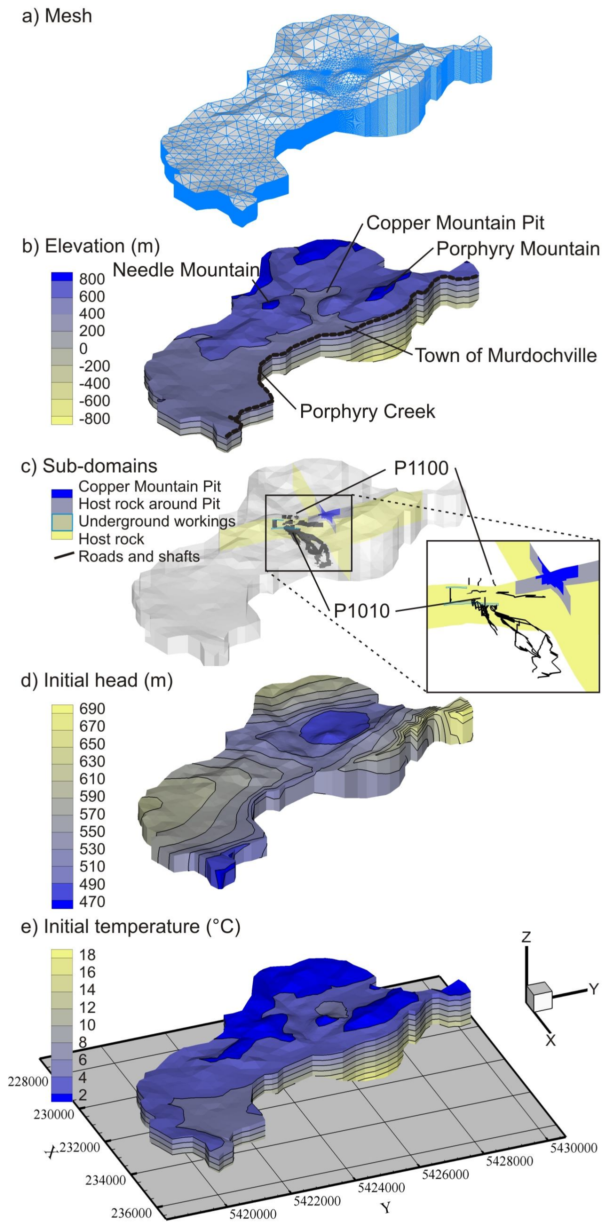


Figure 6.7. Plots of the Gaspé Mines numerical model: a) mesh, b) elevation showing geographic points of interest, c) sub-domains, d) initial hydraulic heads, and e) initial temperatures for transient simulations (Raymond, 2010). Coordinates of the grid in e) are in metres according to the UTM NAD 83 system.

Subsequent simulations were carried out to determine the amount of energy that can be extracted when the district system is operated at a maximum pumping capacity of 0.063 m^3/s (3 780 L/min). Heat extraction and injection rates were determined from the loads of the existing buildings at Murdochville industrial park, which cover a total area of 112,000 m^2, and were multiplied by different factors in different simulations. For each case, the pumping and injection temperatures were verified to ensure that they remain above 5 °C and 2 °C for 50 years to ensure sustainability and prevent freezing in the pipelines, respectively. Operating temperatures for the optimal scenario, where building loads are multiplied by a factor of 3, are shown in Figure 6.8. The annual amount of heat extracted and injected underground is -3,176 MWh and 1,754 MWh, respectively, and represents 71 % and 115 % of the building heating and cooling loads. Simulations therefore indicated that the proposed system can provide more than three times the thermal energy that is currently needed to heat the buildings of the industrial park at Murdochville. Pumping temperatures that stabilized near 5.9 °C during the 50 years of simulation suggested that the maximum energy extraction rate was not reached, but a higher operating flow rate is necessary to extract more energy and prevent freezing in the pipelines. Numerical modelling conducted in this study was shown to provide a valuable tool for decisions regarding the system operation.

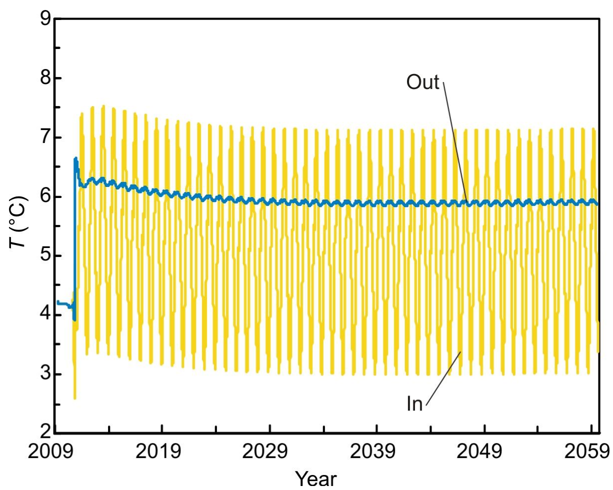


Figure 6.8. Simulation of production (out) and injection (in) temperatures when the district heating and cooling system at Murdochville industrial park is operated at a flow rate of 0.063 m^3/s (3 780 L/min) to provide energy to fulfill three times the current building loads (Raymond, 2010).

6.3.4 Energy Exchange Under the South Waste Rock Dump of the Doyon Mine, Québec

Part of the heat released by the exothermic oxidation of pyrite (Equation 6.1) at mine waste rock dumps is commonly transferred by conduction to the dump basement, where increased subsurface temperatures have been observed. The length of closed-loop ground heat exchangers, used with ground-coupled heat pumps, can be reduced when they are installed in a subsurface warmer than typical geological environments if the system is designed according to peak conditions of the heating season. The water circulating in the heat exchangers can remain at an equivalent minimum temperature when compared to a system with longer heat exchangers and a lower subsurface temperature. The installation cost of a ground-coupled heat pump system can therefore be reduced in the presence of enhanced subsurface temperature, such as that found below oxidizing mine waste dumps. Heat transfer has been simulated with the finite element model HydroGeoSphere (Therrien et al., 2010) to determine possible bore length reduction if vertical ground heat exchangers were installed beneath the South Waste Rock Dump of the Doyon Mine, Québec (Raymond, 2010). This waste dump has been constructed from 1983 to 1987 during the exploitation of two open pits and covers an area of 549,400 m^2. Production of acid mine drainage was first observed in 1985 and its environmental impact was extensively studied (Lefebvre et al., 2001a; Lefebvre et al., 2001b). Geothermal energy resources associated to the waste rock and the underlying host rock are evaluated at 1,680 TJ (Raymond et al., 2008). Results of the geothermal studies at the Doyon Mine are given below. The potential to install such systems in Canada is significant because many waste dumps with possible heat generation have been left in place after exploitation of open pit mines.

Conductive and convective heat transfer at a single ground heat exchanger was simulated for two different numerical models; the first one being a site with no waste dump and the second a site with a waste dump (Figure 6.9). For both models, a single ground heat exchanger that is part of a ground-coupled heat pump system enclosing several heat exchangers was simulated. The length of the vertical borehole containing the exchanger was 98 m. In the second model, the borehole containing the exchanger is located at the toe of the waste dump. It is preferable to install the borehole at the toe of the dump to avoid interference with other activities at the site like remediation, which can involve installation of an impermeable cover at the surface of the dump. The cover is used to reduce water and oxygen inflow to mitigate the oxidation of pyrite and the production of acid drainage.

Typical thermal properties for the subsurface near the Doyon Mine and for the South Waste Rock Dump were used in both models. Thermal conductivities of the subsurface host rock, the overburden and the waste rock material were determined from thermal response tests and are 3.8 W/m-K, 1.8 W/m-K and

2.2 W/m-K, respectively (Raymond et al., In Press; 2011; 2010a). One kilometre away from the waste dump, the undisturbed subsurface temperature was 5.1 °C near surface and increased with depth according to a geothermal gradient of 0.005 °C/m, which was measured in an exploration hole (Raymond et al., 2008). These temperatures and gradients were used for initial conditions to simulate subsurface heat exchange in the model without a waste dump. In the second model with the waste dump, initial temperatures were determined from a preliminary simulation of heat generated by the waste rock and were verified against field measurements. Heating and cooling loads assigned to the ground heat exchanger for both models were determined according to the loads of a typical two-floor mine building that covers 4,181 m^2 and can be located near the site. The annual heating and cooling loads assigned to the ground-coupled heat pump of that building, having a hybrid system with both ground-coupled and air source heat pumps, were 362 MWh and 234 MWh, respectively. The fraction of the building loads assigned to the exchanger was varied between simulations to determine the minimum number of boreholes required for the outlet temperature to remain near 0 °C during peak heating months.

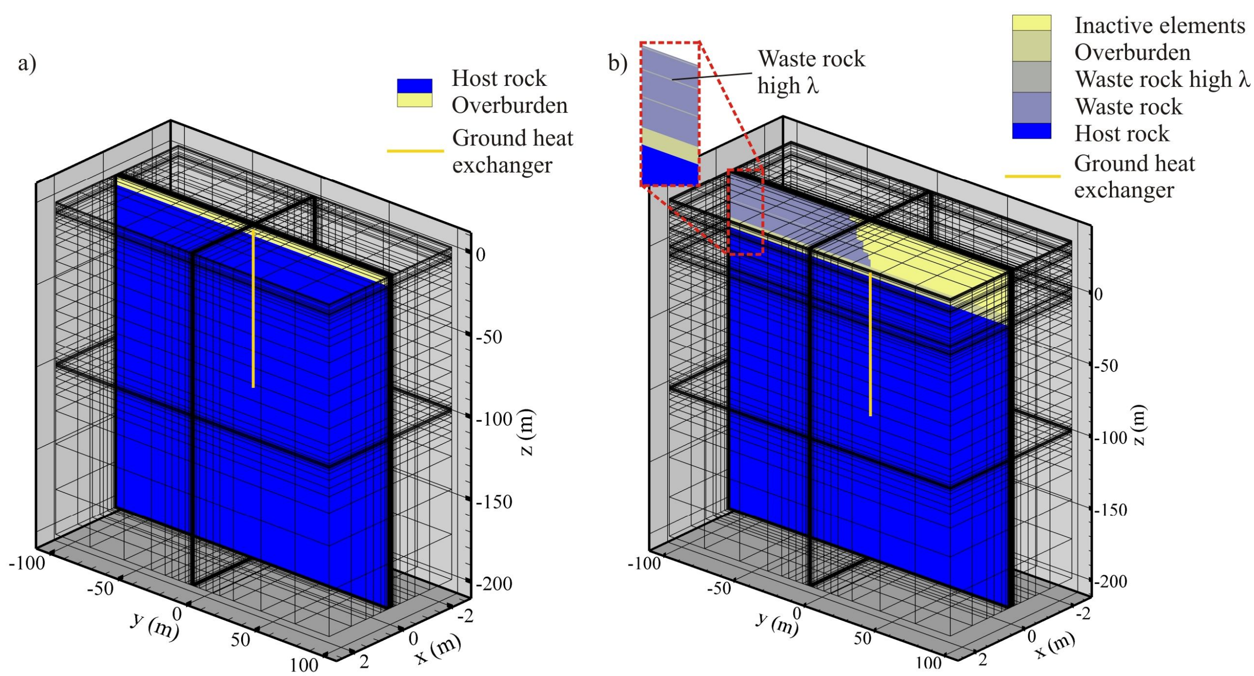


Figure 6.9. Finite element mesh used to simulate a ground heat exchanger for a) a subsurface without waste dump and b) for a subsurface overlain by a waste dump. The vertical cross-sections show the model sub-domains and the location of the ground heat exchanger (Raymond, 2010).

Outlet temperatures that were predicted for heat exchangers of systems operated with and without the waste dump are shown in Figure 6.10. The simulations covered a 25-year period, which corresponds to the approximate life of the heat pump unit. The system located in the subsurface without the waste dump required 13 boreholes compared to 9 for the system installed below the waste dump. Simulations with a reduced heat generation rate, representing a scenario where an impermeable cover has been installed over the dump to mitigate pyrite oxidation, also indicated a minimum of 9 boreholes to maintain a minimum outlet temperature near 0 °C. Heat generated by the waste rock and stored in the subsurface underneath the dump provided a setting that allowed reduction of the borehole length by about 31 % compared to the case without the waste dump. The potential to install such systems is significant because at least 55 waste rock dumps producing acid drainage have been inventoried in Québec alone (Raymond et al., 2008). Similar geothermal operations could also be investigated at other types of waste sites that produce heat, such as ash landfills.

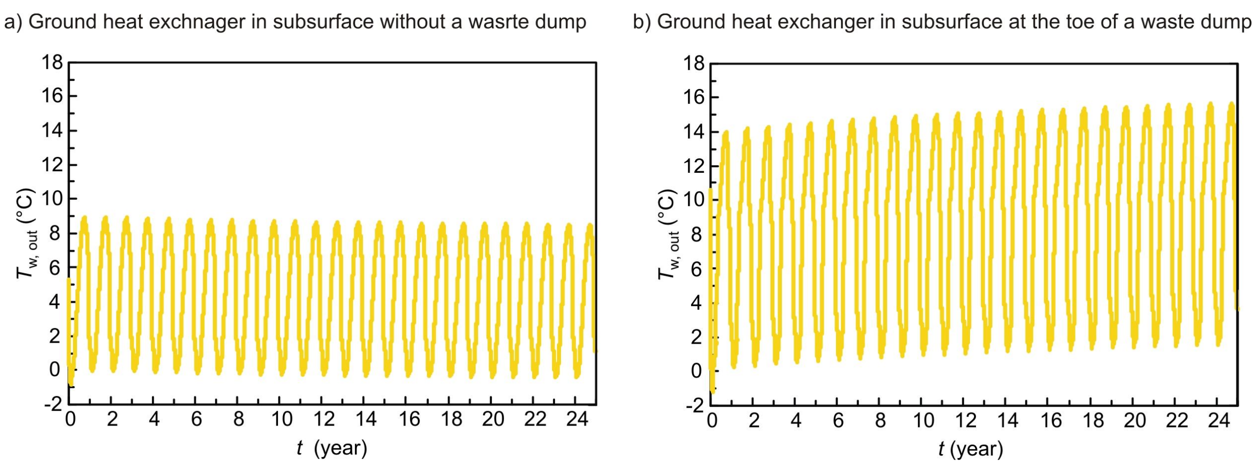


Figure 6.10. Simulated outlet temperature for a ground heat exchanger located a) in a subsurface without a waste dump where the building loads are distributed over 13 boreholes, and b) in a similar subsurface at the toe of a waste rock dump where the building loads are distributed over 9 boreholes (Raymond, 2010).

6.4 INVENTORY OF GEOTHERMAL RESOURCES ON MINE SITES

Records of past mining activities can provide information to estimate low-temperature geothermal resources in mining environments. For safety reasons, provincial governments have created inventories of most abandoned mine sites. Inventories for British Columbia (Government of British Columbia, open file 2003-3), Alberta (Energy Resources Conservation Board, 2010), Saskatchewan (Saskatchewan Environment, 1989; 2001; 2002; 2003), Québec (Arkay, 1992), and Nova Scotia (Arkay, 1992) have been used to produce maps showing the geothermal potential of abandoned mines. The inventory of geothermal resources on mine sites is currently incomplete because data are missing for several provinces. Data shown on the maps can nevertheless help identity abandoned mines near cities.

For each site, the location of the mine and the mass (tons) of ore removed were listed. The amount of water contained in the mines was estimated with ore production records, according to the methodology given in Section 6.2.3 and assuming that all the mines are totally flooded. The volume of water in each mine was then used with Equation 5.6 to estimate the geothermal resources available for heating using heat pumps. The temperature difference, δT in Equation 5.6, was assumed equal to 5 K at all sites regardless of their depth because information on mine depth is often difficult to obtain. This temperature difference is representative of shallow to moderately deep mines and is a conservative estimate for deep mines, where warm water temperatures (10 to 20 °C) are expected, like at Springhill. In the case of a deep mine, a larger temperature differential can be achieved. The geothermal resources associated with each site are additionally characteristic of the energy that can be injected underground during cooling. For this application, the temperature differential is negative and can be larger. However, maps showing the cooling potential have not been produced since results are expected to be similar, except that the potential can be two to three times larger. Based on the energy resources estimated for heating purposes, all sites have been plotted on provincial maps with a color scale that indicates the size of the resources (Figures 6.11 to 6.15).

6.4.1 British Columbia

Data for underground and open pit mines were available in British Columbia to evaluate geothermal resources of abandoned mines that were exploited for base-metals, industrial minerals and coal (Government of British Columbia, open file 2003-3). A total of 208 open pit and 424 underground mines have been included in the inventory, which reveals geothermal resources that sum to 12,878 TJ (Figure 6.11). Of the open pit mines, 48% are base-metal, 43% are industrial mineral, and 9% are coal. Underground mines are mostly base-metal, which constitutes 84% of the underground mine sites reported, followed by coal, 13%, and industrial mineral, 3%. The total geothermal resources for open pit and underground mines are 8,075 TJ and 4,803 TJ, respectively. Areas of most interest are in southern British Columbia, near Abbotsford, Penticton and Kamloops, and on Vancouver Island, near Nanaimo. These cities have populations ranging from 35,000 to 125,000 inhabitants. The size of the mines reported can be large, and 61 sites exceeding ten million tons of ore removed were listed. The geothermal potential associated with flooded mines in British Columbia, having the most complete inventory of all provinces, is therefore large and averages 39 TJ and 11 TJ for each site with open pits and underground excavations, respectively.

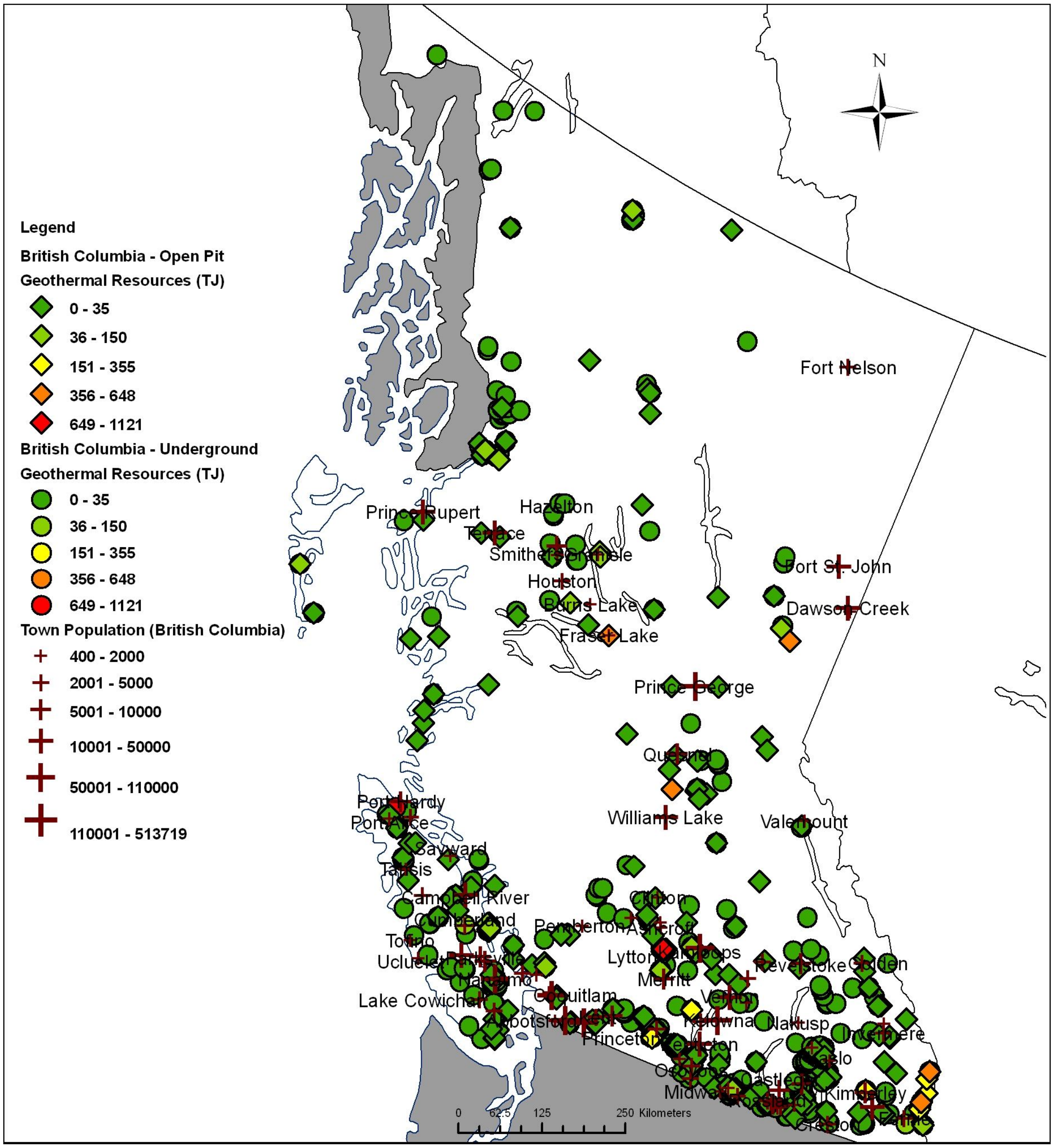


Figure 6.11. Geothermal resources of flooded underground and open pit mines in British Columbia. Data for base-metal, industrial mineral and coal mines are shown on the map.

6.4.2 Alberta

A list of open pit and underground mines, where coal extraction occurred, is available for Alberta (Energy Resources Conservation Board, 2010). The total geothermal resources enclosed at the 231 open pit and 818 underground mines in this list are 4 835 TJ (Figure 6.12). About 79% of these resources are hosted by open pits. Mines located close to important cities are found in Central Alberta near Edmonton and Parkland County and to the south near Medicine Hat. The population of these cities is above 29,000 and Edmonton is the largest with more than 730,000 inhabitants. Abandoned mines of Alberta are moderate in size and include 88 sites where more than one million tons of ore was removed. Average geothermal resources for underground and open pits mines are 1.24 TJ and 16.5 TJ, respectively.

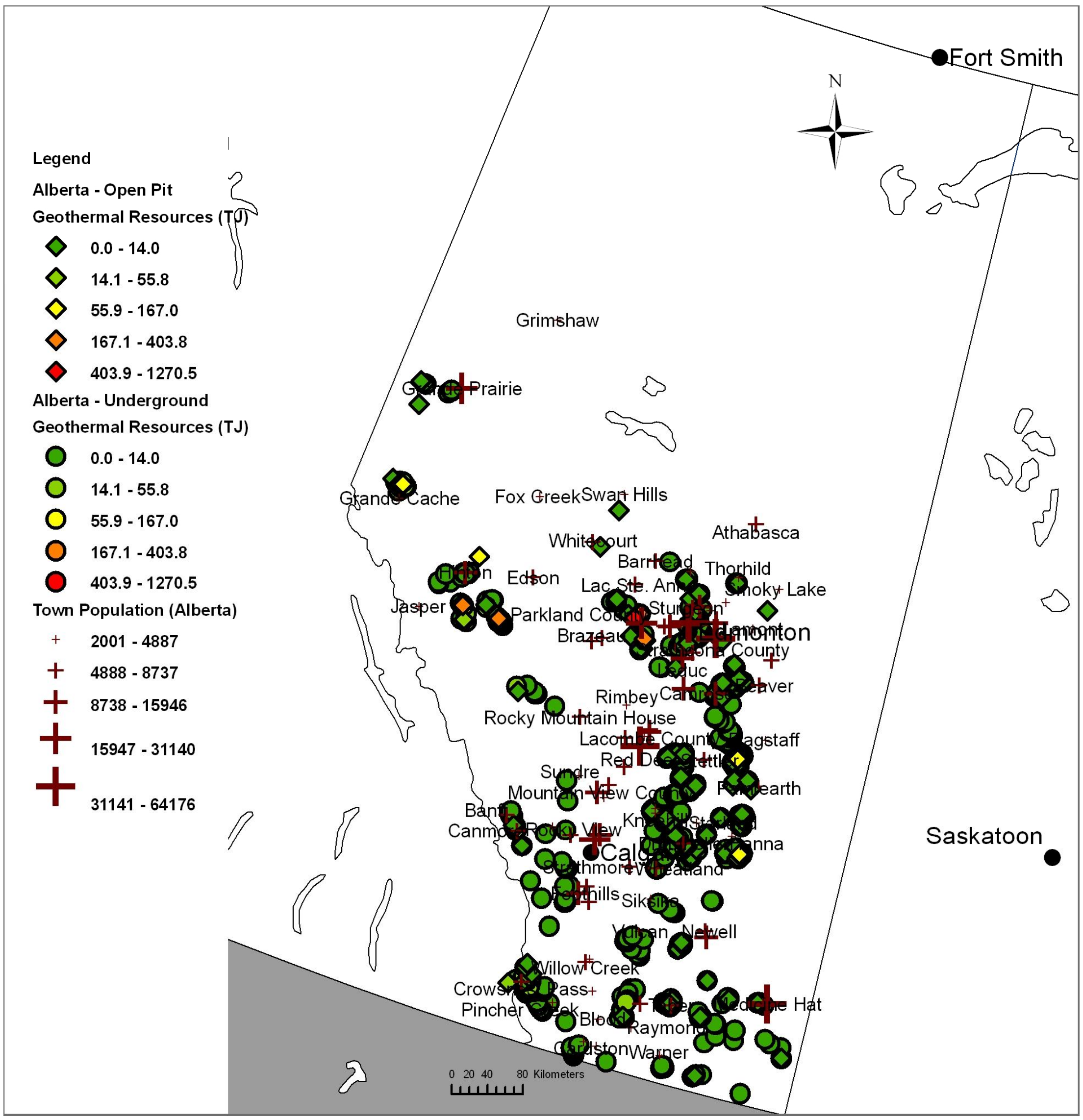


Figure 6.12. Geothermal resources of flooded underground and open pit mines in Alberta. Data for coal mines are shown on the map.

6.4.3 Saskatchewan

Only underground mines with base-metal extraction were available to conduct the inventory in Saskatchewan (Saskatchewan Environment, 1989; 2001; 2002; 2003). The total geothermal resources of the 24 underground mines reported are 17.2 TJ. The abandoned mines are located in northern Saskatchewan, near small towns with populations under 3,000 inhabitants. Most of these mine sites are small, and 83% have less than one million tons of ore removed. The average geothermal resources per site are 0.72 TJ.

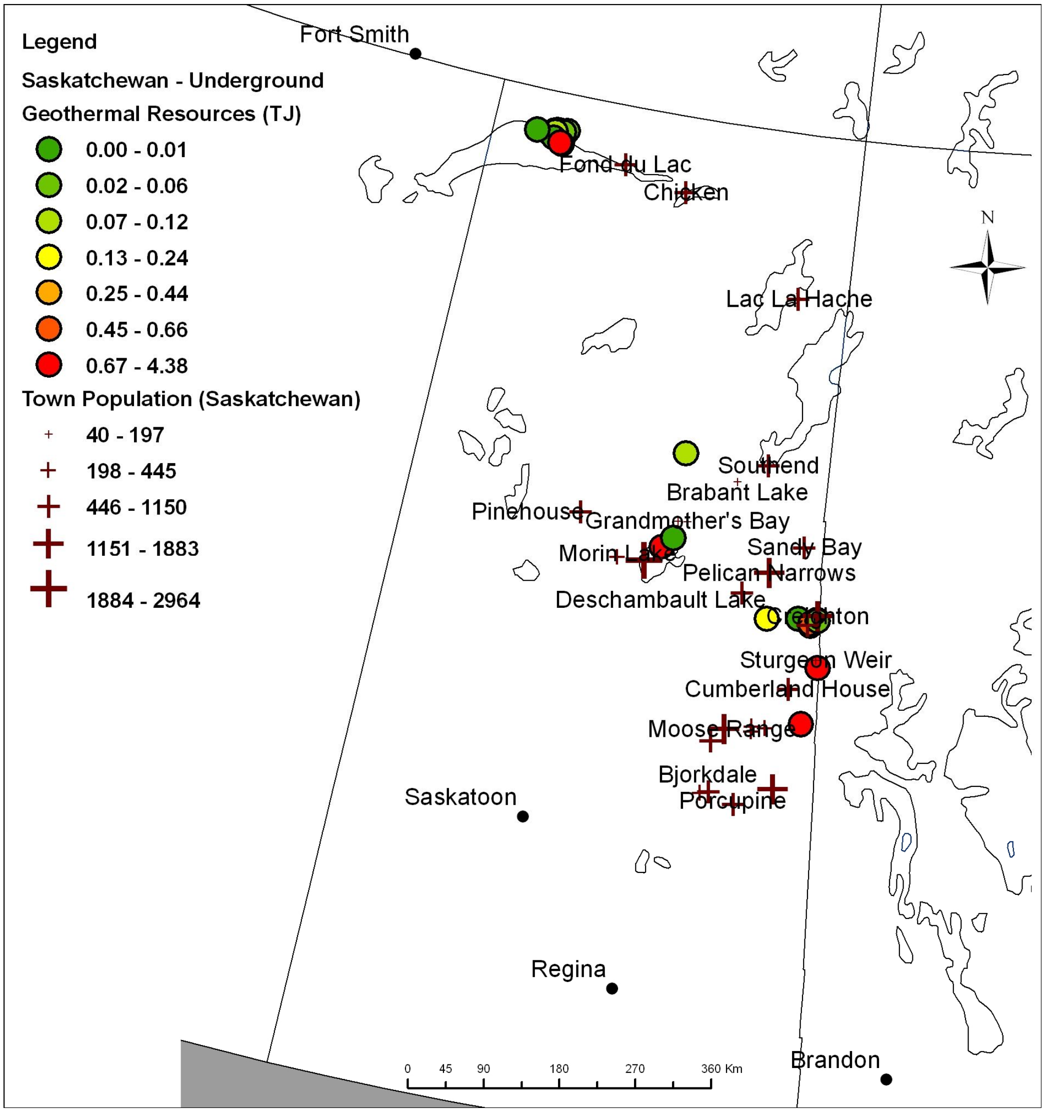


Figure 6.13. Geothermal resources of flooded underground mines in Alberta. Data for base-metal mines only are shown on the map.

6.4.4 Québec

Data presented for the province of Québec are based on the inventory carried out by Arkay (1992), which concerned underground mines only and indicated the occurrence of 165 sites that had production of base-metals or industrial minerals. Arkay (1992) used the data to assign a geothermal potential to each mine located within 10 km of a community and for which more than 5×10^5 tons of ore were extracted. Of all the mines showing a potential, 156 sites contained enough information to evaluate their geothermal resources (Figure 6.14). The sum of the geothermal resources evaluated for these underground mines, which are 90% base-metal, is 887 TJ. Areas with the highest geothermal potential are located in southern Québec, near Sherbrooke and Thetford Mines, and in western Québec, near Rouyn-Noranda and Val D'Or. The population of each of these four cities is above 25,000, and Sherbrooke is the largest with a population of about 147,000 inhabitants. Most mines in southern Québec were exploited prior to 1950 and are relatively moderate in size, with a few million tons of ore removed at most. Many mines in western Québec were developed after 1950 and tend to be larger than mines in southern Québec, with a mass of ore removed exceeding at some sites ten million tons. In addition to mines shown on the map, Arkay (1992) inventoried 94 exploration sites that contain small excavations. These sites are mostly located in southern Québec, near Sherbrooke and between Montréal and Gatineau. The province of Québec therefore has a great geothermal potential associated with large to medium flooded mines, having an average geothermal resources of 5.86 TJ per site and in proximity to cities.

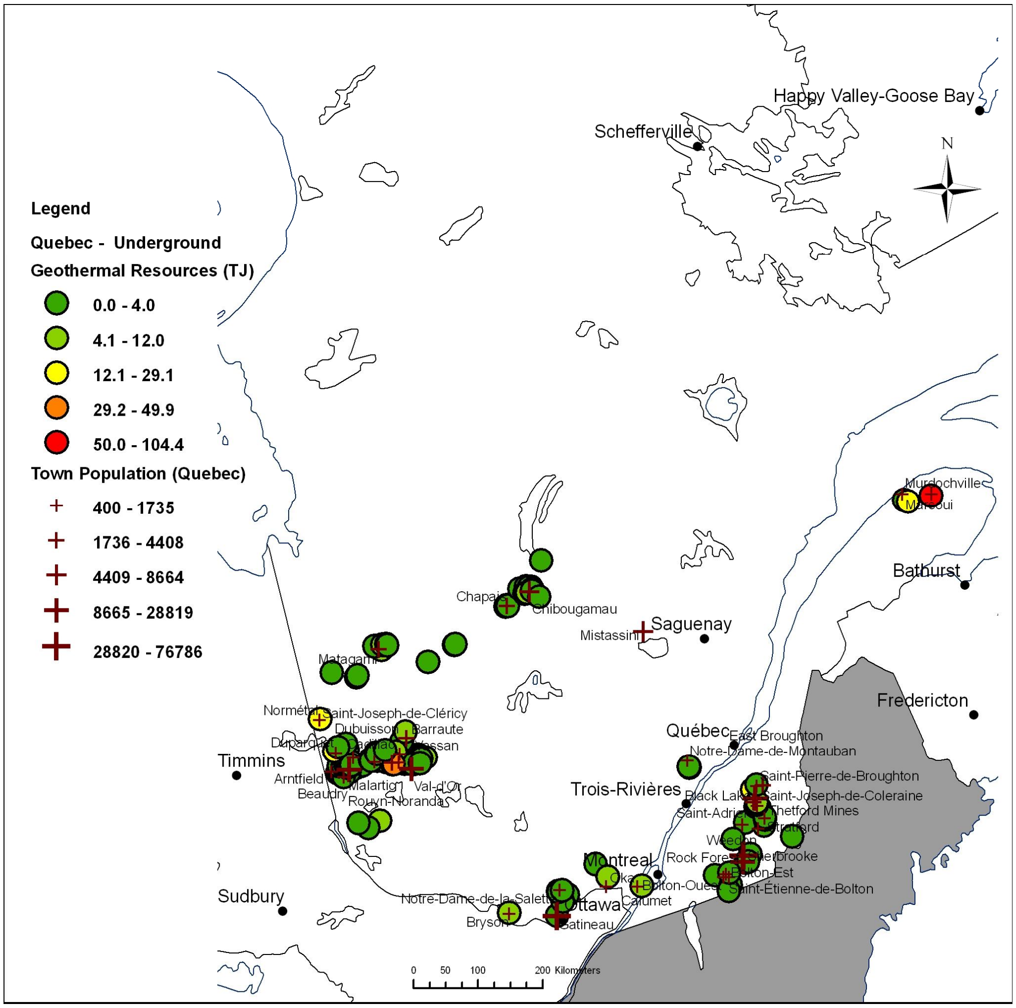


Figure 6.14. Geothermal resources of flooded underground mines in Québec. Data for base-metal and industrial mineral mines are shown on the map.

6.4.5 Nova Scotia

A total of 179 base-metal and 213 coal mines with underground excavations that have been abandoned were inventoried in Nova Scotia by Arkay (1992). Only base-metal mines were plotted on the map to estimate resources (Figure 6.15) since coordinates for coal mines were not available in the database. Of the base-metal mines, 59 sites showed a geothermal potential and sufficient data to compute the associated geothermal resources. Most of the other 120 sites did not have a geothermal potential due to their small size, typically having less than one thousand tons of ore removed. The sum of geothermal resources for the 59 base-metal mines is 24.8 TJ. Many of these base-metal mines were developed prior to 1920 and are relatively small. Tons of ore removed are below one hundred thousand for 42 of the 59 sites considered in the geothermal resource calculations. Mines in Nova Scotia, on other hand, are often located within less than 1 or 2 km of a small city. That proximity can promote the development and use of the resources by the communities. The greater Halifax area contains several small mines and represents one of the areas of interest in the province. Additionally, the 213 coal mines not shown on the map are prime targets for geothermal energy because they can contain deep underground seams. For example, underground seams at the Springhill and the Sydney mines reach depths of 1,350 m and 915 m, respectively. Some coal mines are located near the cities of New Glasgow, Sydney and Glace Bay, each having a population greater than 20,000 inhabitants. The potential to develop geothermal resources from mines in Nova Scotia, averaging 0.42 TJ per site for base-metal mines of interest, is attractive due to the proximity of the mine sites to communities.

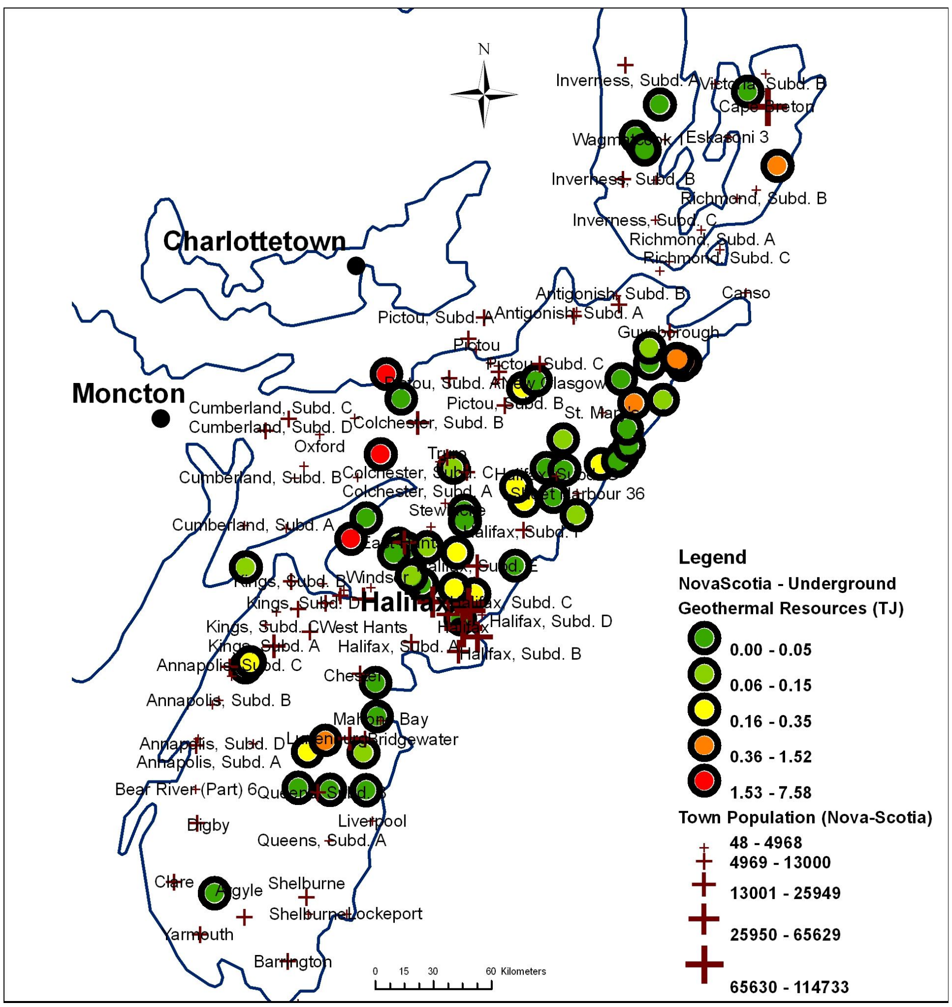


Figure 6.15. Geothermal resources of flooded underground mines in Nova Scotia. Data for base-metal mines only are shown on the map.

6.5 DISCUSSION AND CONCLUSION

The operation in Springhill, which was one of the first in world, started a few years after the 1970's energy crisis, when oil prices dramatically increased and several countries identified a need to develop alternative energy resources. Oil prices eventually dropped and interest in heating and cooling buildings with geothermal energy from mines remained low during the 1990's. Recent increases in energy prices and commitments to reduce emissions of greenhouse gases have revived the interest in geothermal energy. New studies reported in this chapter have assessed the geothermal potential of other flooded mines, like Britannia (Ghomshei and Meech, 2003) and Gaspé (Raymond and Therrien, 2008; Raymond, 2010). The payback period for these projects varied between 2.5 to 8 years, which illustrates that mine sites can make geothermal technologies competitive compared to other sources of energy. Additional benefits include the reduction of greenhouse gas emissions, which is evaluated in Chapter 10. Research projects are currently underway to investigate more mine sites in Canada, including the Con Mine near Yellowknife in the Northwest Territories (Ghomshei, 2007) as well as diamond mines in the Northwest Territories and base-metal mines near Sudbury, Ontario (Raymond et al., 2008). The project reported for Con Mine is expected to become an important showcase for geothermal energy and mines as the City of Yellowknife will receive between $10 to 20 M from the Clean Energy Fund of the federal government to develop a district heating system networked to downtown buildings. The research planned will generate additional knowledge to better assess the geothermal potential of mines and predict the system operation to maintain sustainability.

The inventory carried out in British Columbia, Alberta, Saskatchewan, Québec and Nova Scotia revealed 2,262 abandoned mines. All sites with sufficient data to estimate an energy content indicated that geothermal resources total 18,642 TJ. Such resources can be used for heating purposes with heat pumps. The total resources hosted by mines in Canada is assumed to be underestimated since several sites were lacking data to properly assess energy content. In addition, lists of abandoned mines for some provinces were not available. Among the abandoned mine sites shown on provincial maps (Figures 6.11 to 6.14), potential targets for geothermal operations were identified near cities or major communities. These targets are located from coast to coast near Nanaimo, Abbotsford, Kamloops, Penticton, Parkland County, Edmonton, Medicine Hat, Rouyn-Noranda, Val D'Or, Sherbrooke, Thetford Mines, Halifax, New Glasgow, Sydney and Glace Bay. Geothermal resources hosted by mines can be exploited within a few kilometres of mine sites only. Pipelines can rapidly increase the cost of a project when the distance to carry the mine water increases. The project in Springhill was successful due to the proximity of the coal seams, with some located directly beneath the town. It is therefore important to target mine sites near cities or major communities, while considering further development of geothermal resources in mining environments. Such developments can provide benefits to the population, like the diversification of the energy supply and a decrease in the use of conventional energy sources.

The inventory of abandoned mines reported in this Chapter could be extended to other Canadian provinces to estimate their geothermal resources. For example, the province of Ontario has a long mining history and the geothermal potential in its mining environments is assumed to be significant, although no maps were presented because of incomplete data. The inventory could also be expanded beyond flooded underground mines and include more open pits as shown on the maps of British Columbia and Alberta (Figs. 6.12 and 6.13). In addition, water retention ponds and mine waste storage facilities can be considered. Raymond et al. (2010b) demonstrated that these mining features also have a geothermal potential and can contribute to reduce the installation costs of geothermal heat pumps used for space cooling and heating. Maps of geothermal resources and online databases need to be available to policy makers and businesses. This would permit development of additional sites and subsequently offer heating and cooling energy savings to end users as seen in the operation at Springhill, Nova Scotia (Jessop et al., 1995).

7. GEOTHERNAL RESOURCES IN SEDIMENTARY BASINS

7.1 INTRODUCTION

Canada is covered by extensive sedimentary basins (Fig. 3.10). These represent rocks formed by deposition of sediments in ancient oceans, inland sea and river systems. Typically sedimentary basins have significant volume of porous rock that host abundant fluids, dominantly water, but also economic accumulations of oil and gas. Sedimentary rocks typically have low thermal conductivity, meaning that they act as a thermal 'blanket', trapping heat that is generated by radioactive decay elements in rocks which lie underneath the basins. This leads to higher geothermal gradients within the sedimentary basins, such that areas with thick sediment cover can have potential for high temperature water resources.

While sedimentary basins cover extensive regions of Canada, data suitable for analyses of geothermal potential tends to be limited to regions with significant hydrocarbon exploration and production. For this reason we restrict the focus of the remainder of this chapter to the Western Canada Sedimentary Basin.

7.2 WESTERN CANADA SEDIMENTARY BASIN

The Western Canadian Sedimentary Basin (WCSB) covers over 1.4 million km^2 of Western Canada, including parts of Alberta, northeastern British Columbia, the southern Northwest Territories, Saskatchewan, and southwestern Manitoba. The basin forms a western thickening wedge of sedimentary rock, from a zero edge on the eastern margin, up to 6 km thickness under the Rocky Mountains. The WCSB contains one of the world's largest reserves of petroleum and natural gas. Since discovery of the Leduc well in 1946 there has been a significant exploration and production history in the basin. Data derived from the hydrocarbon industry can be used to help characterise the geothermal potential of the basin.

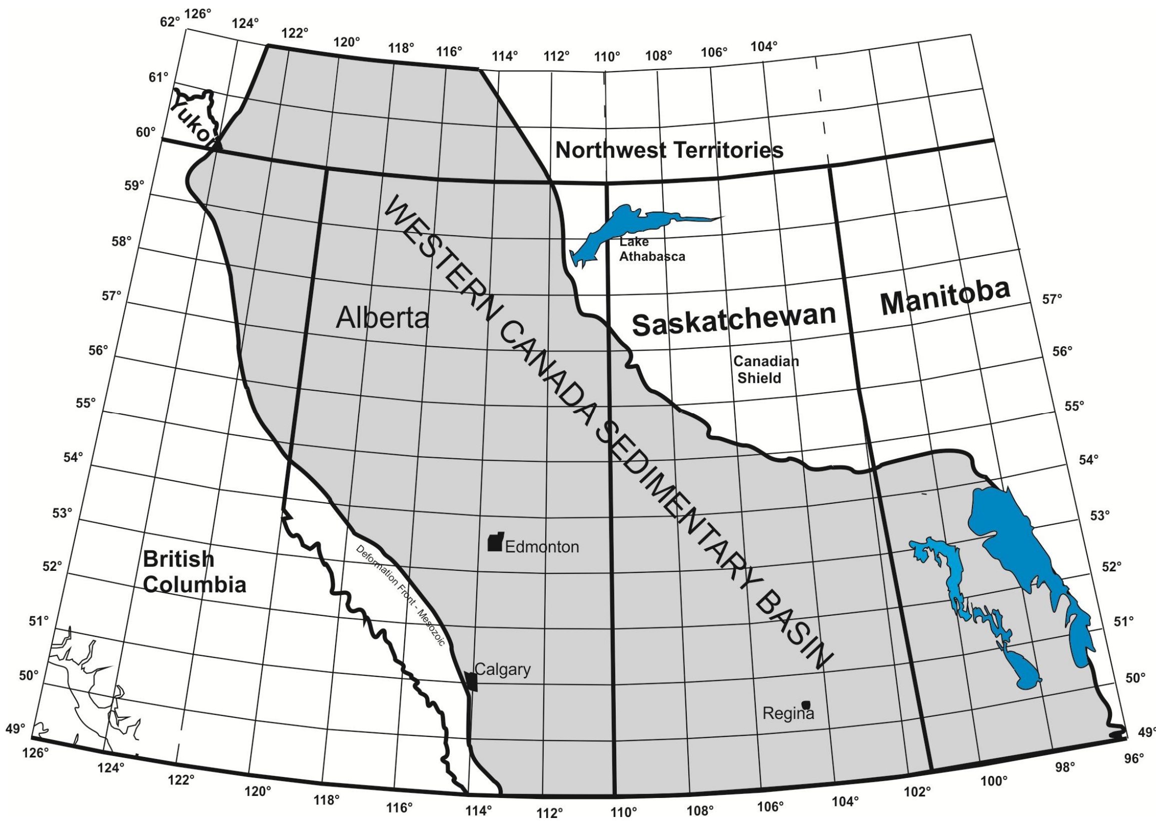


Figure 7.1. Map showing areal coverage of the Western Canada Sedimentary Basin.

7.2.1 Temperature Data

Temperature in sedimentary basins can be difficult to determine. While there are a large number of data, there are significant issues of data quality and availability (many are not in digital form). Despite this, large numbers of temperature measurements can by statistical treatment, give a general picture of temperature distribution and the major regional anomalies.

The distribution of temperature measurements derived from various sources for the WCSB is shown in Figure 7.2. For parts of the basin, there is extensive spatial coverage; however, there are still large areas with limited to no available digital data (paper copy and microfiche records do exist for some of these areas however). The quality of the data varies widely depending on the nature of data and the purpose of the data collection. Figure 7.3 shows the temperature-depth (T-D) relationship in the Western Canada Sedimentary Basin (WCSB). A wide range of temperatures at the same depth indicates variable data quality as well as the variation in the geothermal field across the Basin. These data can be used however to derive local geothermal gradients to observe gradient variations within the basin (Fig. 7.4).

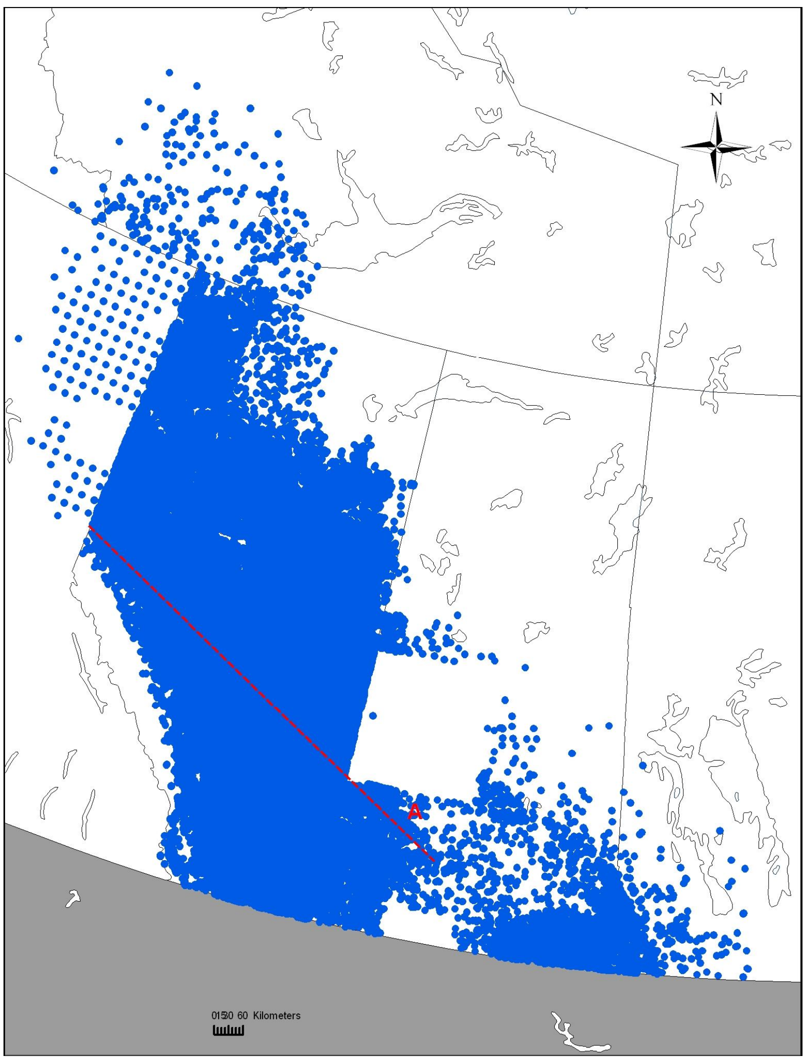


Figure 7.2. Distribution of temperature data compiled from petroleum industry wells from different sources across the Western Canada Sedimentary Basin. The red dashed line shows the line of cross-section in Figure 7.8.

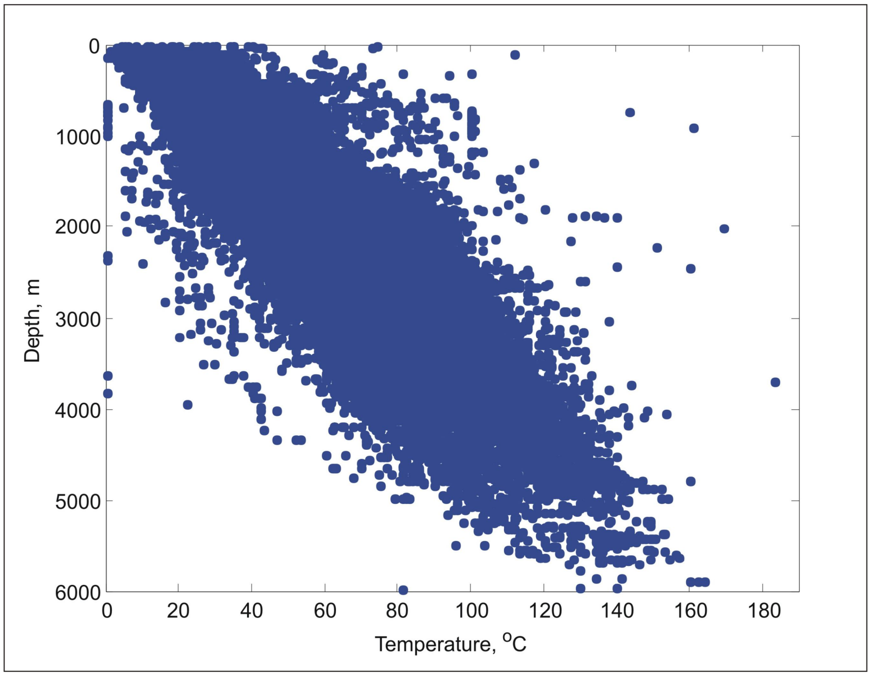


Figure 7.3. Depth-temperature plot of the compiled temperature datasets shows a wide range of temperature variation, suggesting both uncertainty in the data as well as spatial variation of temperature field.

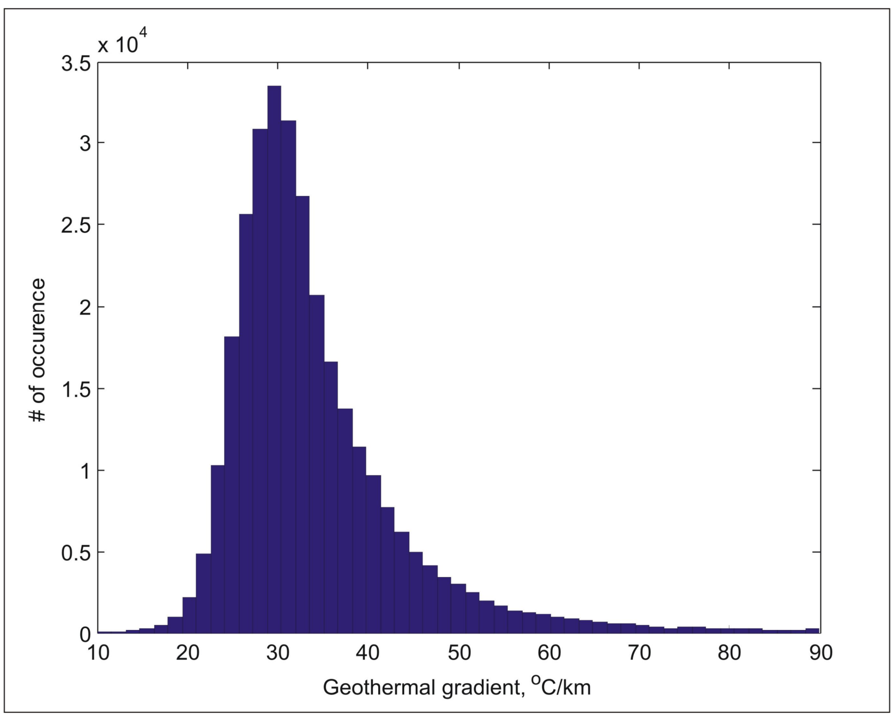


Figure 7.4. Histogram displaying the geothermal gradients for uncorrected BHT well data in Alberta.

The most abundant temperature data in the WCSB are derived from BHTs reported on well log headers of petroleum wells drilled from 1939 to 2000. These are believed to be a representation of the original bottom-hole measurements; however, the temperatures have not been corrected to a thermal equilibrium state before disturbance by drilling. The correction requires additional data on drilling and circulation times that may or may not be recorded at the time of temperature measurement. Typically after drilling stops it is common for mud circulation to continue for a period of time in order to clean and condition the hole. This leads to BHT readings that are less than the true formation temperature. Because all the BHTs are uncorrected for thermal equilibrium, it is likely that the geothermal gradients shown on Figure 7.4 are underestimates of true geothermal gradients. The T-D plot for these raw data is shown in Figure 7.5. The estimated corrected temperatures, from wells with sufficient information to perform corrections, are shown in Figure 7.6. From these corrected temperatures, the range of geothermal gradients with removal of obvious anomalies can be derived as in Figure 7.7.

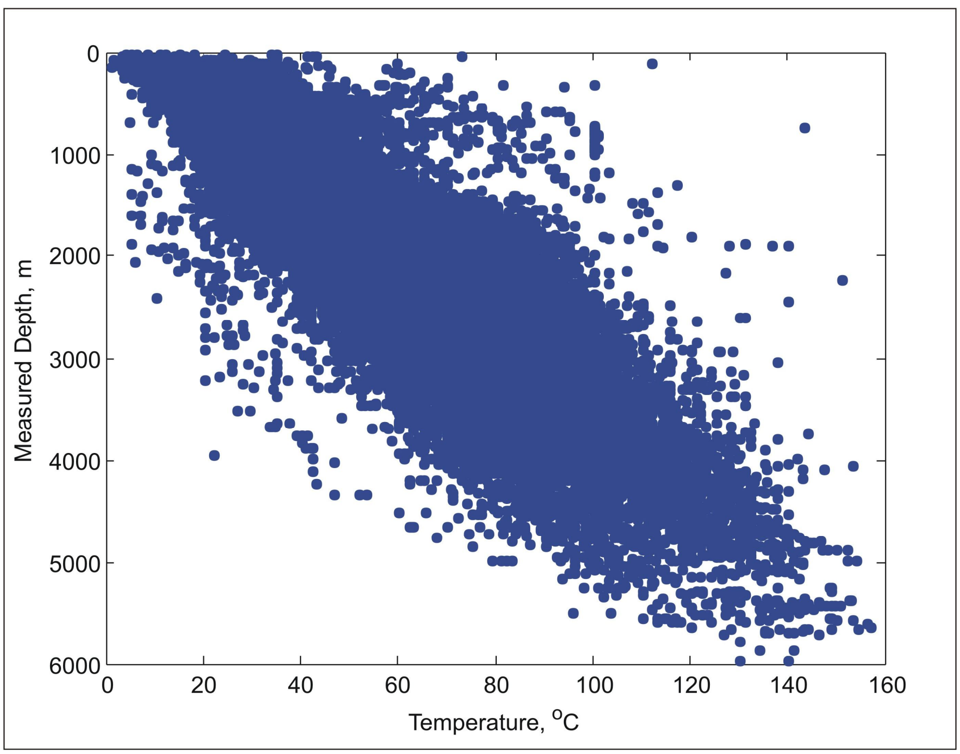


Figure 7.5. Depth-temperature plot for uncorrected temperature data from BHT measurements for wells in Alberta.

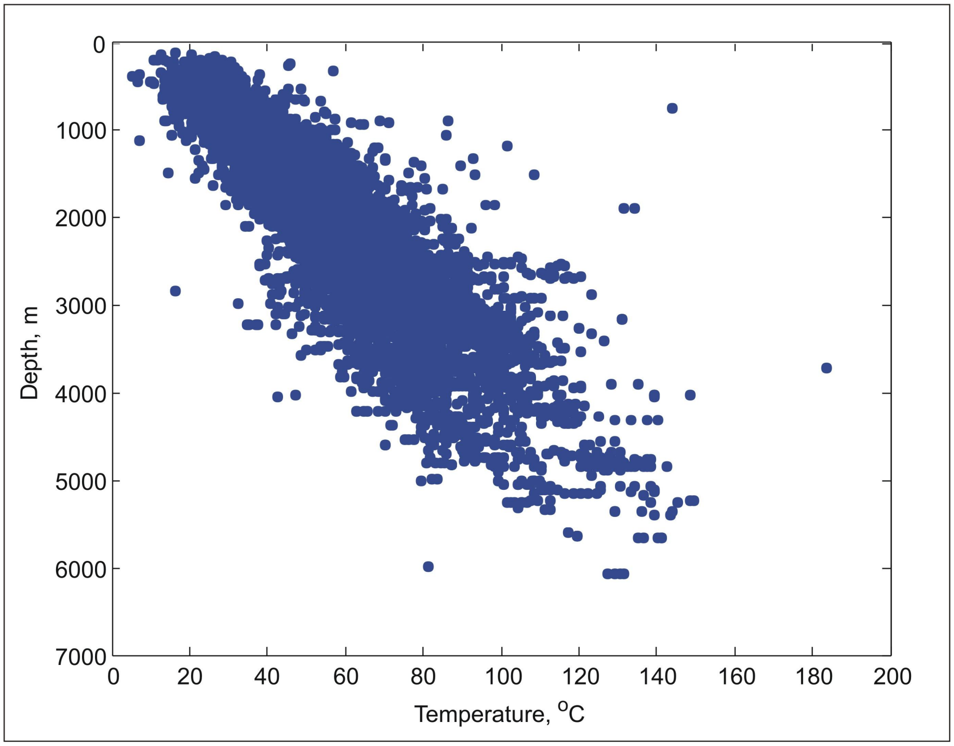


Figure 7.6. Depth-temperature plot displaying estimated corrected temperature data for BHT measurements from wells in Alberta.

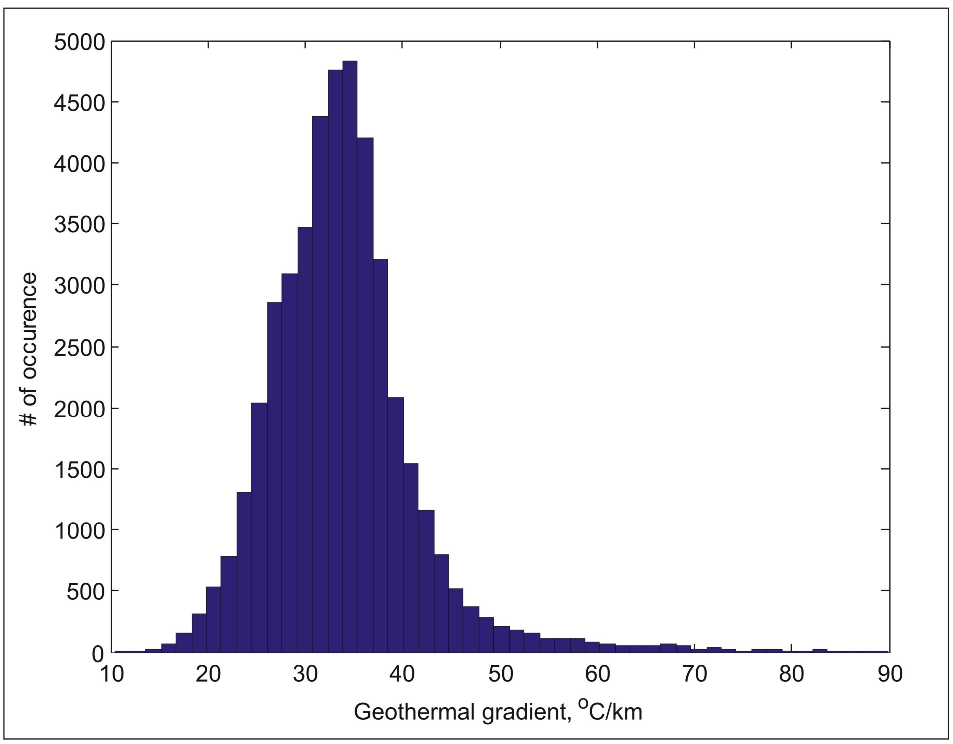


Figure 7.7. Histogram of estimated geothermal gradients in Alberta after removal of obvious anomalies.

These resultant temperature data can be used for characterization of the present day temperature field for geothermal resource assessment and exploration. A northwest-southeast temperature profile through the WCSB (Fig. 7.8) shows a continuous vertical view of temperature variation in the region (see Fig. 7.2 for location).

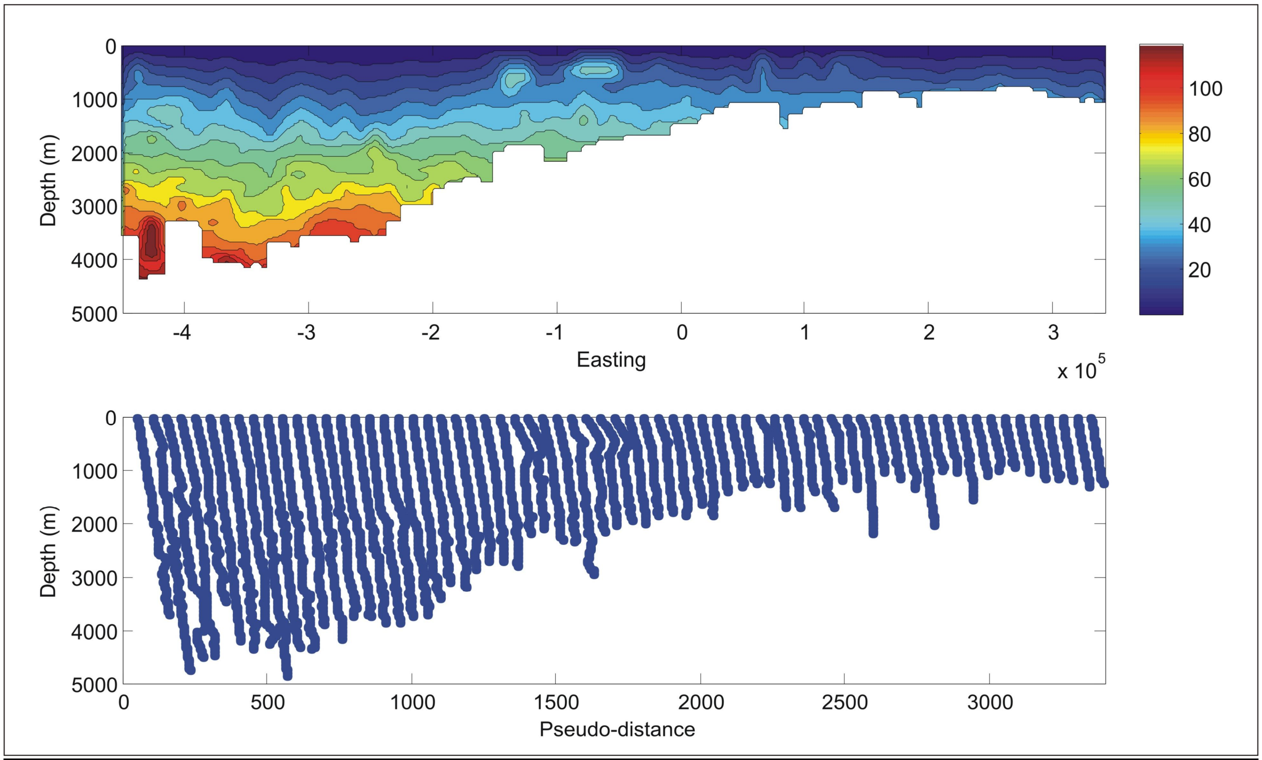


Figure 7.8. Temperature cross section (A) and profile (see Fig. 7.2 for location) showing general characteristics of the present day temperature field. Color bar on the right indicates temperature in °C.

7.3 ESTIMATES OF RESOURCE POTENTIAL

To obtain an estimate of the total energy contained in the formation waters of sedimentary basins it is necessary to adopt some definitions of resources and the limits of economic exploitation. For the present purposes, the classification of resources is based on the system described by Muffler and Cataldi (1976), which is illustrated and described in Jessop (2008a). For the purpose of assessing the useful resource of geothermal aquifers, two temperatures characteristic of the heat extraction system, are defined, as follows.

- The "threshold temperature" is the temperature below which it is not practical to produce water. This may be about 60 °C if a heat exchanger system is used, and may be as low as 10 °C if a heat pump is used. Since temperature normally increases with depth, a low threshold temperature means that it is possible to use shallow aquifers, with great savings in drilling costs.

- The "return temperature" is the temperature at which the water is rejected from the extraction system and returned to the ground. This is the effective base for calculations of heat, and a decrease in return temperature provides an increase in heat supply. This may be 30 °C for a heat-exchanger system. If a heat pump is used, the only fixed limit is the freezing point of the fluid, but each system has its own limiting useful temperature.

In the WCSB, between the latitudes of 49 °N and 60 °N, and between the Rocky Mountains and the exposed Precambrian Shield, the area of sedimentary cover is 1.26 x 10^6 km^2, the average depth is 1,778 m, and the volume of sediments is 2.24 x 10^{15} m^3 (Hitchon, 1968). The total pore volume has been estimated to be 265 x 10^{12} m^3 (Hitchon and Friedman, 1969), which implies an average porosity of 11.8%. Assuming a density of water of 1.0 Mg/m^3, this means that the rocks contain 265 x 10^{15} kg of water. The data of Sproule Associates Ltd. (1976), provides an average geothermal gradient of 33 mK/m.

The generalised isopach map of Sproule Associates Ltd. (1978) has been used to derive a distribution of the depth of the basin. Surface areas have been measured between successive isopachs of 304.8 m (1,000 ft) and the total area is found to be 1.27 x 10^6 m^2 ± 2%, not including the "disturbed belt" of the Rocky Mountain Foothills. A simple volume calculation for each interval yields a total volume of 2.16 x 10^{15} m^3 ± 5%. This figure is about 4% lower than the estimate of Hitchon (1968), but this difference is within the limits of accuracy of the present method.

It is assumed that the specific heat is 4,200 J/kgK, and that the mean surface temperature is 4 °C. The total useful heat in the water of the basin was calculated for a range of values of the threshold and return temperatures, and the results are shown in Figure 7.9. The heavy red line shows the limiting energy when the threshold and return temperatures are equal. For practical and economic reasons, this level of utilisation is unlikely to be achieved, and curves are shown for return temperatures that are 20 K, 40 K and 60 K lower than the threshold temperature and for constant threshold temperatures. Given that depths are averaged over each zone, that surface temperature is averaged over the whole area, and that estimates of rock and pore volumes, specific heat and density are all subject to error, the resulting energy estimates are probably subject to a possible error of 20 %.

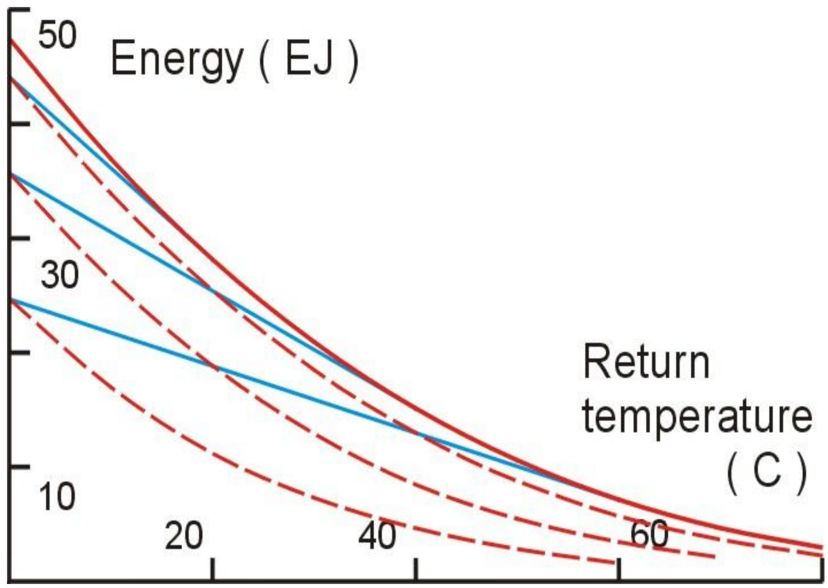


Figure 7.9. The amount of heat in geothermal water beneath the WCSB as a function of threshold and return temperatures. Return temperature is plotted on the horizontal axis. The continuous red line shows the limiting energy when the threshold and return temperatures are equal, i.e. the total energy above the return temperature. The dashed red lines show the available energy for threshold temperatures that are 20 K, 40K and 60K higher than the return temperature. Blue lines show the energy above constant threshold temperatures of 20 °C, 40 °C and 60 °C as a function of return temperature.

The values in Figure 7.9 are the energy in the water only. The heat in the rock is not included. Given the above assumptions, the heat in the solid rock is 3.7 times as great as the heat in the water. As pointed out by Hutchence et al. (1984), the heat in the rock is drawn upon during circulation by the conventional well doublet method, so that at least part of the heat in the solid rock is part of the accessible resource base at any location.

Reasonable threshold and return temperatures in geothermal systems that do not employ heat pumps are 60 °C and 30 °C, respectively, and for systems that include heat pumps these are reduced to 40 °C and 10 °C. It may be seen from Figure 5.18 that the total heat in the basin that meets or exceeds these criteria is 16 x 10^{21} J and 31 x 10^{21} J, respectively.

These figures represent the part of the accessible resource base in the water of the porous sediments. Only a small fraction of the accessible resource base may be regarded as economic resource with current available technology. The presence of the energy does not imply that it is economically and technically feasible to exploit more than a small portion of it.

By the definition of Muffler and Cataldi (1978), the accessible resource base includes all heat to a depth of 7 km, regardless of the material holding the heat. Since the maximum depth of sediments in the WCSB is about 5 km, all heat in the water residing in the pore space of these sediments and all heat in the solid fabric of the sedimentary rock is included in the accessible resource base, as so defined, but the heat in the solid rock is not included in the above calculations. There is also a portion of the Precambrian basement between the lowermost sediments and the limit at 7 km that holds part of the accessible resource base as hot dry rock. By adding these three components, the total accessible resource base of the WCSB, to a depth of 7 km, is 1.8 x 10^{24} J. Without major developments in drilling and the technology of extraction, the heat in the Precambrian basement will never be part of the truly accessible resource base.

7.3.1 Estimation of Local Resources

The above estimate of the geothermal resource depends on assumptions of uniform geothermal gradient, porosity, and thermal properties of the water and the rock. It takes no account of variations of these factors, and so it must be refined for use on the local scale. The magnitude of the accessible resource base at any single location depends on the nature of the strata below that place, particularly the nature of the aquifer formations. The distinction between residual and useful resources depends on the depth to the aquifer, the reservoir pressure, the thickness, and permeability of the host rocks. The distinction between economic and sub-economic depends on the local demand for energy, the technology to be used, and the cost of development of the geothermal resource compared to costs of other sources.

The best geological conditions are found in ancient reef systems or in extensive thick sandstone units. The most probable locations for energy demand are in or near large centres of population, where the need for space heating is the highest. The next most probable areas are those where low-grade heat is useful for industrial processes, including agriculture or horticulture. The first of these categories may be defined by proximity to towns and cities, but the second is very difficult to define, since there are so many unpredictable uses for the energy.

The first step in the estimation of local resources is a review of the data from hydrocarbon wells in the area, preferably over an area of 50 km around the site. From these data, the potential aquifer formations are identified, the thickness, porosity, permeability and temperature of these aquifers are estimated. The best fit between the possible sources and the needs of the surface installation is identified. The information from the hydrocarbon wells will probably not provide all the data needed, as pointed out by Gorrell (1984).

Of the major cities of the WCSB footprint, geothermal resources are best known at Regina. Information has been assembled during the course of a feasibility study for heating at the University of Regina (Vigrass et al., 1978), and as the result of the drilling of an exploratory well on the campus of the University (Vigrass, 1979). The temperature at the base of the target aquifers is about 60 °C. The best source of geothermal water is the Basal Clastic Unit, at depths from 2,045 m to 2,208 m, but there are other aquifers at shallower depths and of less favourable temperature and water supply.

The net sand aquifer in the Basal Clastic Unit has a thickness of 113 m, divided between the Winnipeg and Deadwood Formations. Average porosities are 15.7 % and 14.7 %, respectively, giving an integrated porosity x thickness of 15.6 m. Salinity of the water is about 12 %, mainly sodium chloride, giving a density of 1.09 Mg/m^3 and a specific heat of 3,600 J/kgK (accounting for the salinity of the formation brines). From these data, the heat content of the water of these formations, per unit area is 61×10^6 J/m^2. Since the Basal Clastic unit is reasonably uniform in character and the area of the City of Regina is approximately 130 km^2, this amounts to a geothermal resource below the city of 19×10^{15} J. This quantity may be regarded as a useful, discovered resource.

There is a very large resource of heat in the WCSB and other smaller resources in other basins. Most of this resource is too remote from potential users to be of interest, but some of it is beneath cities where it could easily be exploited for domestic or industrial space heating. The technology is simple: it has been demonstrated in France and in other countries. Expertise and industrial capability could easily be developed in Canada.

The resource has been conclusively proved at Regina, but has not been used there. One well has been drilled that could have produced hot water, and a second well could be drilled. The first well is 28 years old, and its maintenance is unknown. It may be suffering from corrosion, so one may not conclude that it is in the same condition as it was in 1979.

Geothermal development in sedimentary basins requires the drilling of two deep wells at the beginning of the project, and thus suffers from a capital cost at the beginning that must be financed by income generated. Hydrocarbon wells work the same way, but the numbers of wells involved, the continuous process of exploration and development has developed to the point where this is no longer an obstacle to economic development.

8. ENHANCED GEOTHERMAL POTENTIAL IN CANADA

8.1 INTRODUCTION

Enhanced (or Engineered) Geothermal Systems (EGS) are reservoirs that have been created to extract economical amounts of heat from low permeability and/or low porosity geothermal resources. The EGS concept is well discussed in the recent MIT report and elsewhere (Tester et al., 2006, Blackwell, 2006; Blackwell et al., 2007) and has driven increased interest in development of this geothermal potential. EGS systems have significant advantages over conventional hydrothermal systems commonly used across the world (Barbier, 2002), that must be located near easily-accessible hot water resources. EGS systems do not require in-place water nor an initial high permeability of the reservoir, making application of this technology largely only restricted by adequate heat supply at reasonable drilling depths. Practical use of EGS resources has been demonstrated in several projects, including Soultz-sous-Forêts, Alsace, Hot Dry Rock in Europe (BGR, 2008), and the Cooper Basin in Australia (Tester, 2006). Additional research on EGS systems is underway in other countries (Huenges, 2008; Baujard et al., 2008; Clauser, 2006).

Here we provide an initial evaluation of EGS as a potential renewable energy supply for Canada, and define EGS ‘target’ areas of high priority for future, more detailed regional to local studies. These results could eventually establish the scientific basis for future drilling and EGS demonstration projects.

8.2 BACKGROUND

While normal geothermal systems involve producing hot waters from depth, Enhanced Geothermal Systems can extract economical amounts of heat from low permeability and/or low porosity geothermal resources. Here water is injected and fractures are induced to form subsurface heat exchange systems. The heated water is then produced from a parallel well where heat can be used at surface to generate electricity. A key attraction of EGS is that it removes the risk associated with exploring for hot fluid reservoirs. Other associated risks, such as induced seismicity and deep drilling costs, may offset this however.

In Switzerland EGS is referred to more precisely as geothermal heat mining (GHM), whereas historically it has been referred to as hot dry rock (HDR). In Australia the term 'heat farming' is used to recognize that after heat is extracted from a rock body, temperatures will recover if left undisturbed, and the same unit can be 'farmed' for heat again at a future date. An EGS project has several stages:

1. Drilling an injection well to the depth required to reach the desired temperature.
2. Fracturing the rock by hydraulic stimulation.
3. Creating and testing of the storage capacity (3D seismic).
4. Drilling a production well for a doublet system or two production wells for a triplet system (one injection + two producing). Directional drilling technology is required to create some 600 m distance from the injection well to allow a large enough induced heat exchange system in the subsurface.
5. Creating fracture connectivity between the injection and the production wells.
6. Extracting thermal energy from the rock by injecting cool water through the injection well and producing hot water and/or steam from the production wells.

8.3 METHODS FOR EGS ASSESSMENT

The main methods used to estimate the geothermal heat available to be farmed (mined) with an injection/producing well are outlined in Majorowicz and Grasby (2010a; 2010b). To characterize deep geothermal conditions, high precision depth-temperature logs, in addition to variable quality point measurements (bottom-hole temperatures, drill stem test temperatures, etc.), were compiled for the main geological provinces of Canada: sedimentary basins, the Canadian Shield, and the Canadian Cordillera. From these data, as well as depth-temperature maps in Chapter 5, information on geothermal gradient, heat flow, geothermal energy potential, and prediction of temperatures beyond the depth range of observation were derived.

To estimate the thermal energy, or heat content, a 4 x 4 km rock mass, 1 km thick (16 km^3 total volume) was considered, which is at an initial temperature of T_o (°C). If this rock mass of volume V and density ρ is cooled through a temperature difference of $\delta T = T-T_o$ (°C) to a reinjection temperature of 30 to 50 °C (achievable if thermal water is used in heating, drying, balneology, or other processes before reinjection (Barbier, 2002), then the heat removed is given by (also Equation 5.6):

$$Q= \rho C V \delta T \tag{8.1}$$

where a reasonable average value of density, ρ, is 2,550 kg/m^3, and heat capacity, C, is 1,000 J/kg °C. This is consistent with parameters used by the MIT report on EGS potential in the US (Tester et al., 2006; Blackwell, 2006).

The quantity of thermal energy released from a 16 km^3 rock volume with initial temperature 150 °C was then calculated. If this rock mass is cooled through a temperature difference of 120 °C to a final temperature of 30 °C, then the heat removed Q (in Joules (J)) is given by:

$$Q = (2550\ kg/m^3)*(1000\ J/kg\ °C)*(16\ km^3)*(150 – 30\ °C) = 5\ x10^{18}\ J \tag{8.2}$$

Using this approach the quantity of thermal energy, which could potentially be released from a volume of deep-seated rock (termed here in-place resource), can be mapped to illustrate patterns of highest energy content (primary target zones). The total Canadian energy content was also calculated based on these parameters.

8.4 THERMAL CONTENT FOR EGS DEVELOPMENT

The quantity of thermal energy present in the 3 to 4 km depth range across Canada was calculated and the resultant spatial distribution mapped in Figure 8.1. Data points for this calculation are the same for the maps in Chapter 5, and are based on the heat flow data mesh. Values for the areas outside of the data points were interpolated within a 50 km grid limit as with other maps.

The results suggest that in-place thermal energy potential for only one small 16 km^3 block >150 °C is comparable with Canada's annual energy consumption 3 x 10^{18} J (=10 Quads) per year between 1961 - 1997 (Environment Canada, 2008). The actual accessible and usable geothermal energy resource, however, will be much smaller than this calculated in-place resource. The estimate for "conservative" production used by MIT (Tester et al., 2006) is a factor of 0.02 of in-place thermal energy. Using this value gives 1 x 10^{17} J = 0.1 Quads for the same rock volume as above. This would still provide a significant contribution towards Canadian energy consumption, requiring only 100 developments to meet Canada's current energy demand.

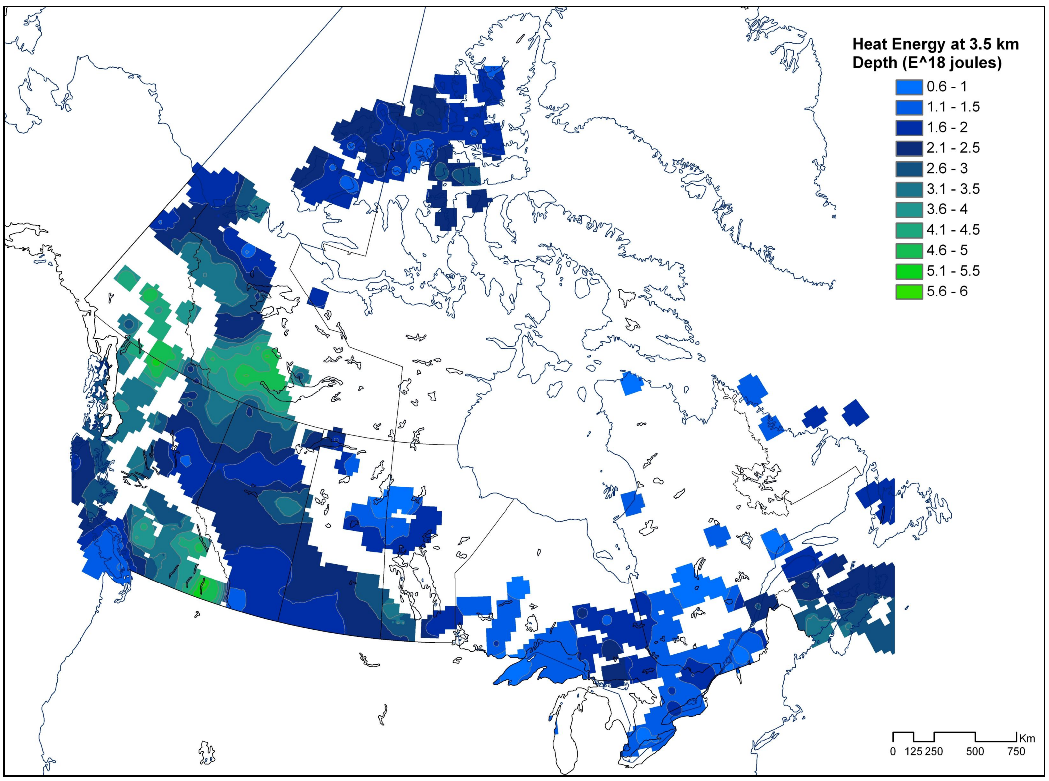


Figure 8.1. Heat Energy at 3.5 km depth.

A similar process was used to define thermal energy potential for a unit 500 m above and below each depth-temperature field. The total quantity of stored thermal energy was estimated for these three depth slices: 3-4 km, 6-7 km and 9-10 km. The in-place geothermal energy content derived from Figures 8.1 to 8.3, representing each slide, is estimated at 1.4 x 10^{24}, 2.9 x 10^{24}, and 4.7 x 10^{24} J, respectively.

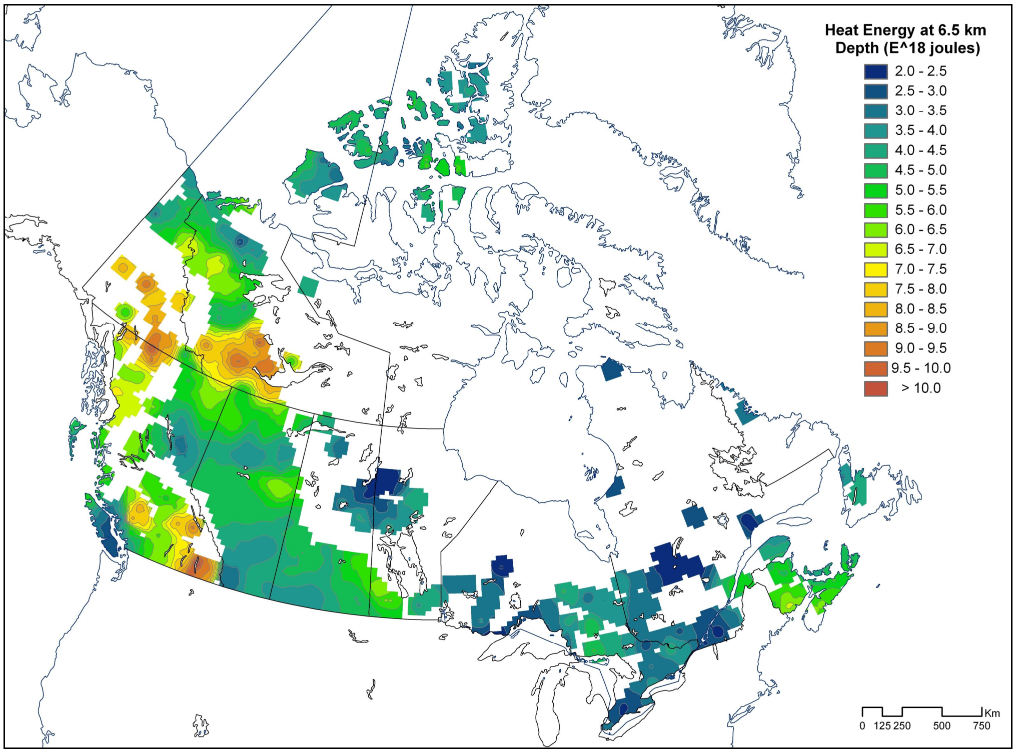


Figure 8.2. Heat Energy at 6-7 km depth.

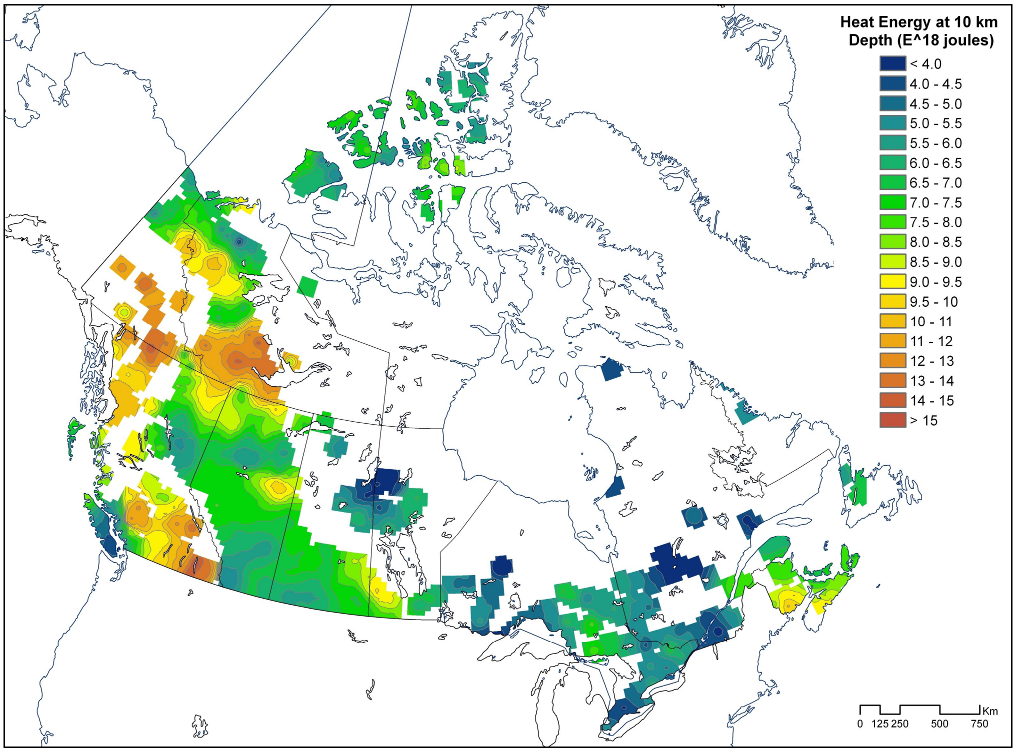


Figure 8.3. Heat Energy at 9-10 km.

These results show a massive energy resource existing throughout Canada, though only a small fraction of this dispersed resource can be used. The key challenge is defining what proportion of this resource is producible and economically viable. While there is more energy at greater depths (up to 10 km) drilling costs increase non-linearly with depth. Of particular interest, however, are areas of high heat-energy potential that underlie sedimentary basins given lower drilling costs through sedimentary rock. However, based on petroleum industry experience, it is now quite common to drill 4 to 6 km deep wells in deeper parts of the WCSB and technology to achieve such depths is readily available.

8.5 HIGH POTENTIAL REGIONS

The Enhanced Geothermal Systems (EGS) potential for thermal and electrical power supply was further examined for communities in western and northern Canada in areas previously defined as having high heat flow (Chapter 5). Specific focus was given to major population centres in western Canada, and northern communities that have high energy costs due to the combination of very low average annual air temperatures and high transportation costs of fuel for heating and electrical generation. Any level of local geothermal development could significantly reduce fuel costs as well as associated greenhouse gas emissions.

Temperature-depth profiles were calculated to determine the depth to 150 °C for a range of most reasonable rock parameters. We focus on 150 °C as it is considered the base temperature for surface electrical generation with binary systems (see Tester et al., 2006). Estimates of temperature at depth are constrained by measured temperatures (Bottom Hole Test (BHT) and Drill Stem Test (DST) data from petroleum wells. Heat flow can also be used to estimate temperature at depths below that currently constrained by drilling data. Figure 8.4 shows the depth to 150 °C across Canada. Temperatures >150 °C are mainly achievable at depths > 4 km. In the case of the WCSB these depths are mainly reached below the sedimentary cover. Thermal conductivity of sediments is usually 2/3 that of crystalline rocks, such that sediments form an effective thermal blanket. Therefore, the increase in temperature with depth (geothermal gradient) in crystalline rocks will be less than that in sediments. A thick sedimentary blanket thus helps decrease the depth required to reach effective temperatures for EGS development. As drilling through sedimentary rocks is typically less expensive, targets under sedimentary basins are also more economically attractive than areas of crystalline rock.

Temperature–depth profiles are constrained at the base of a sedimentary basin by corrected BHTs measured directly at the basement, or extrapolated to the base of sedimentary rocks from the closest data above. These profiles were constructed for 19 population centres, and were chosen for being either: 1) large urban centres that have large electrical and thermal power demand in addition to a good power grid structure, though not necessarily the best geothermal conditions, or 2) smaller population centres located close to areas of high potential for geothermal development based on analysis of heat flow and/or high temperatures at relatively shallow depth.

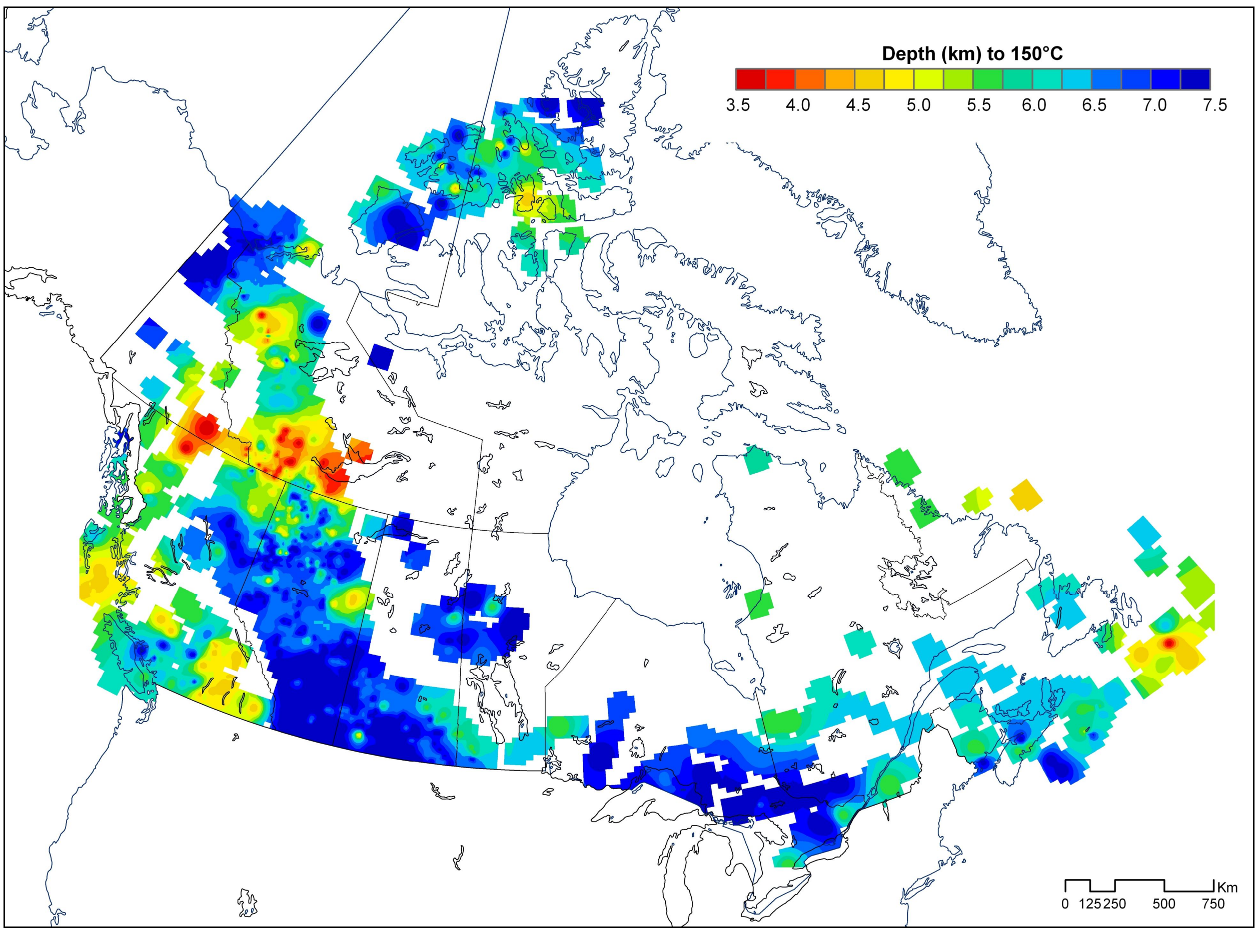


Figure 8.4. Depth (km) to 150 °C temperature.

The modelled geotherms for the WCSB target areas are shown in Figure 8.5. This figure demonstrates the significant role that the thermal blanketing effect of sedimentary cover can play in raising subsurface temperatures. For example, geotherms calculated for Fort Nelson (northeastern BC) and Rainbow Lake (northwestern Alberta) show that 150 °C temperatures can be reached within the upper 4 and 5 km, respectively. These depths are comparable to those in much higher heat flow regions of the Canadian Cordillera (the geotherm for Cranbrook is shown as an example in Figure 8.5).

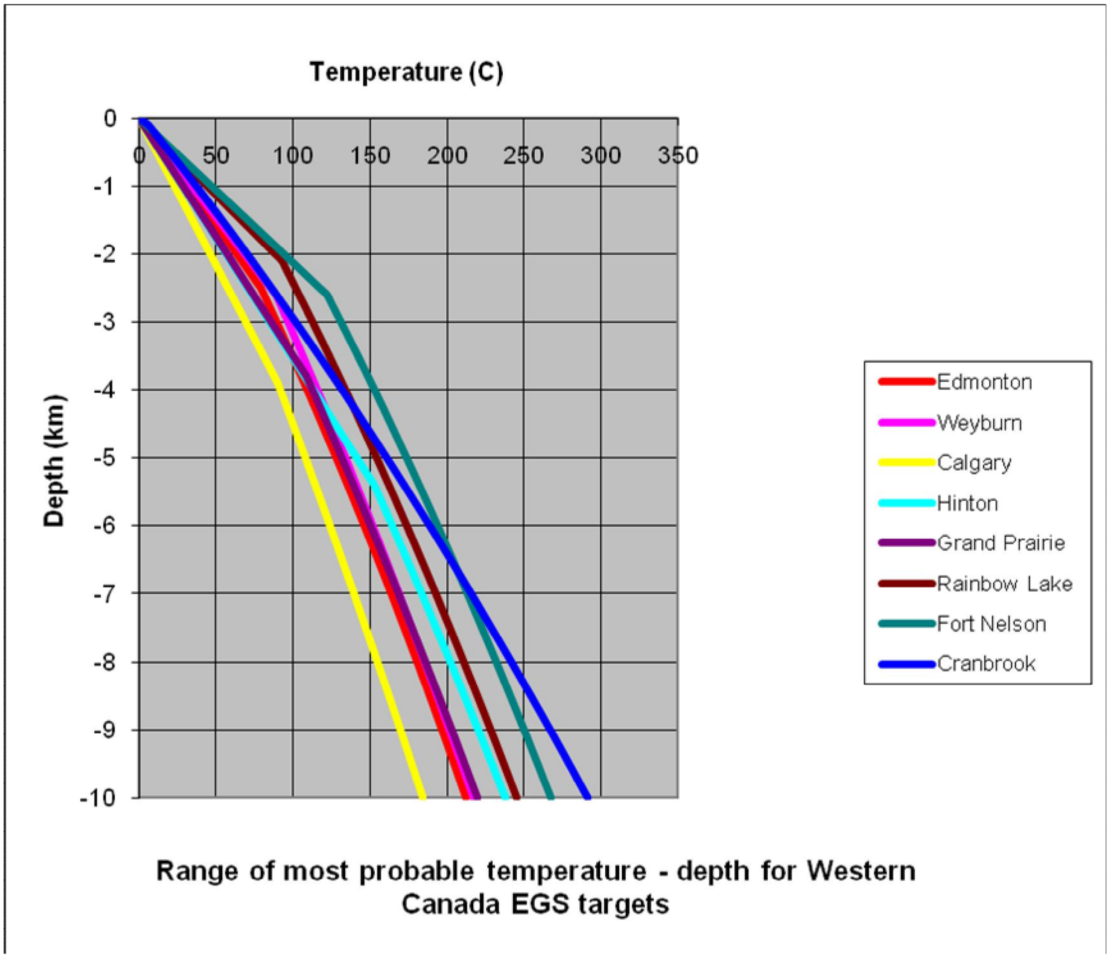


Figure 8.5. Modelled deep geothermal gradients for communities in the Western Canada Sedimentary Basin near areas of moderate to high heat flow. Source: Majorowicz and Grasby (2010b).

In Figure 8.6 we show estimated geotherms for communities in northern Canada. In general the communities examined have good EGS potential, with the exception of the major northern population centres of Whitehorse, Yukon and Yellowknife, NWT. While these two cities occur in areas of modest to high heat flow (Fig. 5.2), the regions are also characterised by high thermal conductivity (2.94 W/m K in Whitehorse; Jessop et al., 1984). Due to this, temperature gradients are low and depths to reach temperature suitable for EGS are high (> 8 km), making development costs likely prohibitively expensive using current technology. Far more suitable northern communities for EGS technology are those in high heat flow areas that also show high temperatures (Fig. 8.6); e.g. Watson Lake, Norman Wells, Fort

Simpson in NWT. These require drilling to depths less than 5 km and as low as 4 km to reach temperatures of 150 °C.

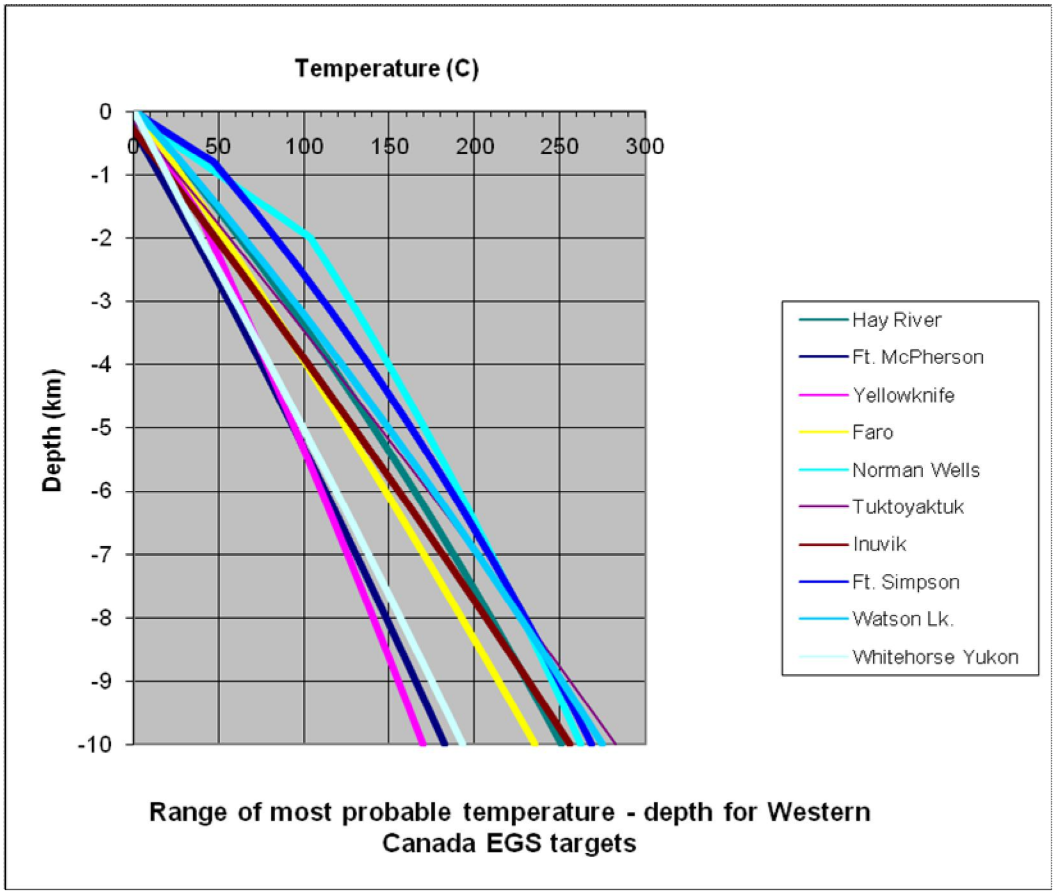


Figure 8.6. Modelled deep geothermal gradients for communities in northern Canada near areas of moderate to high heat flow. Source: Majorowicz and Grasby (2010b).

8.6 CONCLUSIONS

Our results show that Canada has significant potential for EGS development. Similar to the US (Blackwell et al., 2007), the best EGS prospects are in western Canada due to higher overall heat flow. The most promising targets for EGS are in the Canadian Cordillera, with especially interesting areas in southern British Columbia, and in the southern part of the Yukon. In addition, the Mackenzie basin shows promising target areas. Regions of high geothermal energy content in the WCSB occur in northeastern British Columbia and parts of northwestern Alberta. Also, interesting potential targets occur in central

Alberta (including the Lac La Biche high) and in Saskatchewan (Williston Basin high). While the required depths to 200 °C are all deeper than the EGS Soultz, France project (200 °C at 5 km), temperatures as low as 120 °C can be used for EGS systems (Tester et al., 2006).

The analysis of the geotherms shows that the thermal blanketing effect of relatively low thermal conductivity sedimentary rocks (relative to higher thermal conductivity of the basement crystalline rocks) makes deep sedimentary basins in relatively high heat flow areas of the WCSB as attractive for geothermal development as high heat flow belts of the Canadian Cordillera. Regional temperatures suitable for electrical generation, 150 °C or more, can be reached at depths of 3.5-4.5 km in northwestern Alberta and northeastern BC. For communities in the southern Mackenzie Corridor and in southwest Yukon, temperatures >150 °C can be reached at relatively shallow depths of 3.5-5 km.

The results from our estimates of thermal energy potential for only one small 16 km^3 block at a 150 °C initial temperature is comparable with Canada's annual energy consumption 3 to 10 x 10^{18} J = 3 to 10 Quads (where 1 Quad= 10^{18} J) per year between 1961 -1997. The total quantity of thermal energy from 6.5 km is Q = 10^6 Quads. The available heat energy to be 'farmed' at depth is, in reality, only a small percentage of potential heat available due to various technical limits. Even though actual accessible and usable geothermal energy resources will be significantly smaller than the in-place potential, it can still be a very significant energy source. An additional issue is that the energy potential can be only accessed in portions of the Canadian landmass near population centres and grid infrastructure given the high cost of connecting remote areas to the grid. This would limit the economics of some of the highest in-place resource potential. However, given the widespread distribution of geothermal energy, and the high energy content, the potential geothermal resource in Canada is significant.

One issue for northern communities is that the population in areas with good geothermal prospects may be too small to support projected high costs of EGS projects (e.g. the populations of Fort Simpson 1,200; Watson Lake 1,100; Hay River 3,600; Faro 400). These small communities with high heat flow may have better economic geothermal systems associated with lower temperature sources (90-100 °C) to be reached at depths as shallow as 2.5 km. These developments may also benefit from direct production of warm waters within aquifer units of the sedimentary basin.

9. REGIONAL STRESS REGIME

9.1 INTRODUCTION

Information on subsurface rock properties and their confining pressures is required to assess potential for geothermal energy development, especially Enhanced Geothermal Systems (Chapter 6), as it allows prediction of the likely geometry of induced fractures, as well as what pressures are likely to propagate through buried rocks (Tester, 2006). In addition, identifying the orientations of possible open fractures can provide valuable insights for developing geothermal prospects. This knowledge can aid development planning by minimising seismic risk while maximising potential for heat recovery.

The basic data required to understand regional stress regimes are typically available in areas of active petroleum exploration. As such, this analysis is focused on the stress regime of the Western Canada Sedimentary Basin (WCSB)(Mossop and Shetsen, 1994); however, results can be extrapolated to adjacent regions.

9.2 TERMINOLOGY

At a specific point in the subsurface, a rock will be subject to vertical pressure that is usually of a different magnitude to the sideways or lateral pressures. Lateral pressure is likely to be applied unevenly as well, so that the pressure exerted from one direction is different from that exerted from another. Most buried rocks experience lateral compression that is anisotropic (i.e. varies with direction).

The state of stress at a point in the subsurface can be described fully by quantifying the orientations and magnitudes of three orthogonal principal stresses. In most of the geomechanical literature, the principal stresses are defined as σ_1, σ_2 and σ_3, in descending order of magnitude, and are considered to be compressive and numerically positive. This terminology is used to describe confining stresses applied to samples in laboratory tests.

By definition, one principal stress will always be oriented perpendicular to a free surface. The WCSB exhibits low topographic relief over most of its extent so that, on a regional scale, it is essentially flat and forms a free surface with the atmosphere. Hence, it is reasonable that one principal stress will be approximately vertical; in other words, perpendicular to that free surface. This being the case, orthogonality requires that the other two principal stresses be approximately horizontal (Fig. 9.1). Such a stress axis geometry applies to most sedimentary basins, and has spawned the terminology that will be used here. Principal stresses are designated as follows: S_V – vertical stress, S_{Hmax} – larger horizontal stress, and S_{Hmin} – smaller horizontal stress.

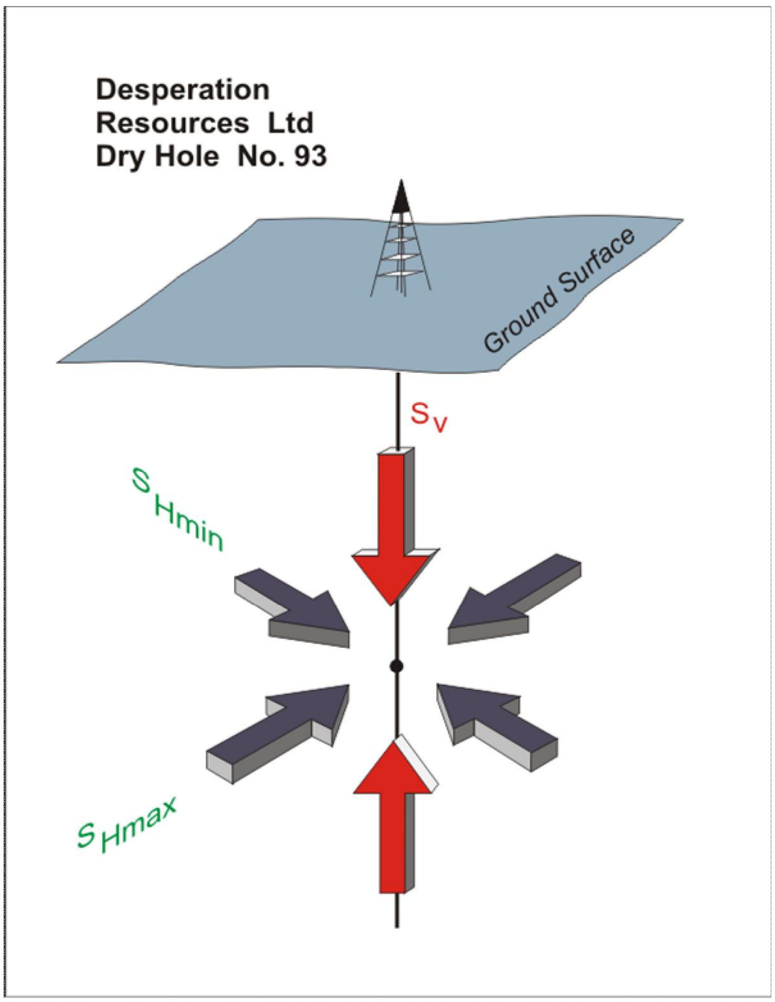


Figure 9.1. By definition, a principal stress must intersect a free surface at right angles. The interface between the ground surface and the atmosphere is a free surface and, where it is relatively flat, one principal stress will be approximately vertical and the other two horizontal.

9.3 MEASURING PRINCIPAL STRESS ORIENTATIONS

As noted above, one principal stress axis in the WCSB is assumed to be vertical (S_V), so measurements concentrate on determining the axes of S_{Hmin} and S_{Hmax}. The majority of horizontal stress axes determined in the WCSB are derived from breakouts (Babcock, 1979). Breakouts are spalled cavities that occur on opposite sides of a borehole wall (Fig. 9.2). They form because a well, being a cylindrical opening in rock, distorts and locally amplifies the far-field stresses, so as to induce localised shear fracturing on the borehole wall (Bell and Gough, 1979; Zoback et al., 1995). When the two horizontal principal stresses are of different magnitudes, the wall rock is squeezed anisotropically. Shear fracturing occurs preferentially on opposite sides of the hole and promotes caving aligned with the axis of S_{Hmin} (Gough and Bell, 1992).

The majority of the breakouts in western Canadian wells have been identified from 4-arm dipmeter log records, where the caliper pads feel the borehole walls. Such dipmeters record the extensions of opposing pairs of pads, as well as the compass azimuths of one of the pads. The basic recognition criteria are unequal extension of two pairs of pads and cessation of tool rotation as the more extended pad pair is confined to the breakout interval (Fig. 9.2). Lateral elongation of boreholes can, however, arise if there is caving on only one side of the well. This will also stop the dipmeter tool from rotating. The phenomenon is known as 'key seating' (Fig. 9.2), and it is typically caused by abrasion on one flank of the borehole wall when the drill string is tripped in and out of a hole. The shorter calipers in key seats often record extensions that are less than the drill bit diameter (Fig. 9.2) and the phenomenon is especially prevalent in inclined wells. Applying a vertical deviation cut-off of 5^o removes most possible key seats from a breakout population. Valid breakout populations have been recognised in 231 wells in the WCSB (Bell et al., 1994; Bell and McLellan, 1995; Sigma H Consultants, 2002; Hamid, 2009; Hawkes and Hamid, 2009).

Horizontal stress axes have also been established in the WCSB by: anelastic strain recovery - 2 wells; differential strain curve analysis - 1 well; hydraulic fracture orientation - 3 wells; microseismic monitoring - 2 sites; overcoring measurements - 5 sites; updip bedding plane slip - 2 sites and waterflood breakthrough - 2 locations (Bell et al., 1994). All are generally in agreement with the in-situ stress axes inferred from breakouts.

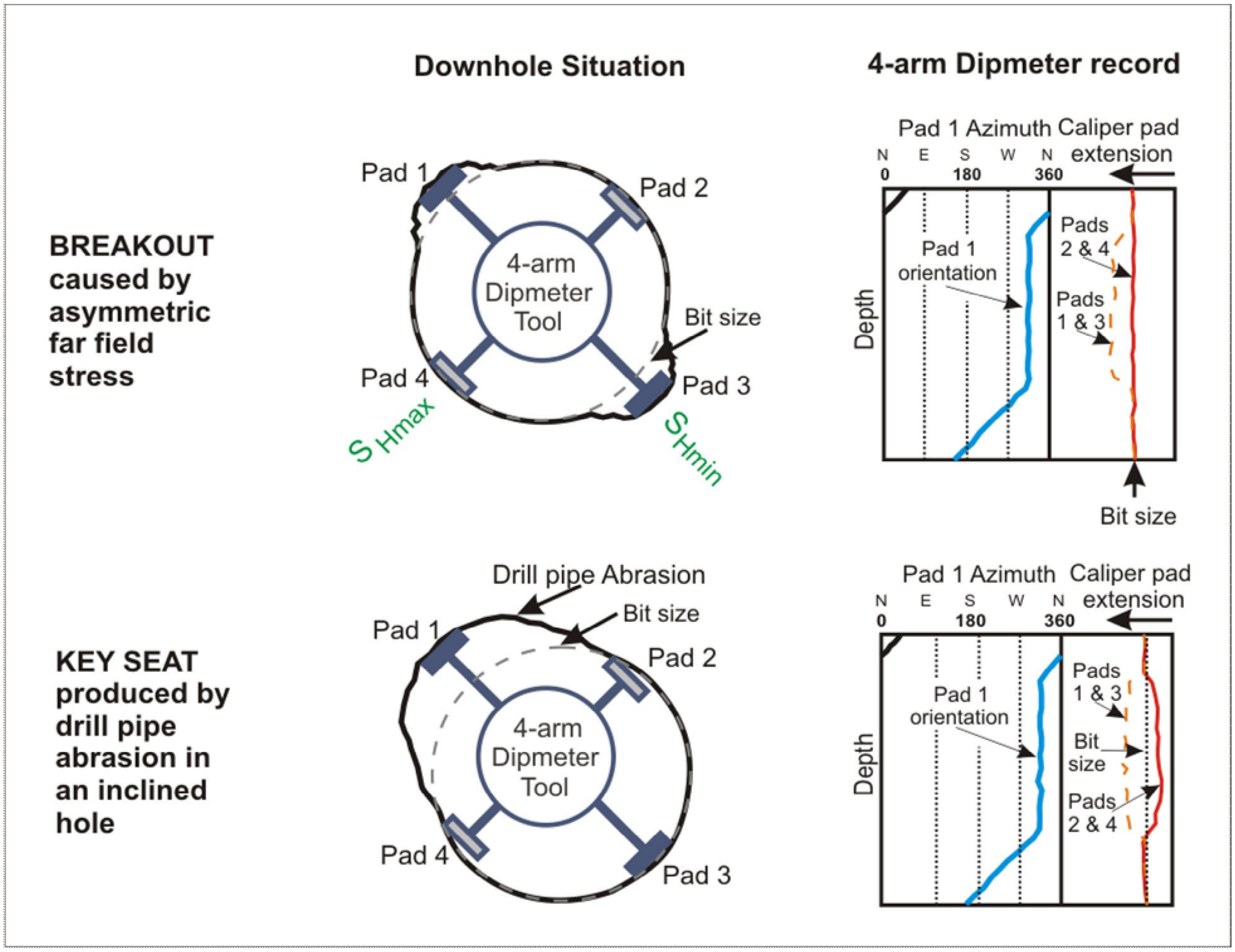


Figure 9.2. Downhole views of stress-induced breakout caving and key seating that is probably caused by drill pipe abrasion on a borehole wall. Note the differences in pad extensions recorded on the uncomputed 4-arm dipmeter logs.

Breakouts in western Canadian wells show little variation in orientation with depth or with stratigraphy. Well 13-19-069-09W6 in northern Alberta provides a good illustration of the directional consistency typically exhibited by breakouts (Fig. 9.3). In this well, a 4-arm dipmeter was run between 2940.6 and 4052.1 metres KB (Kelly Bushing). Twenty three separate breakout intervals, with a net thickness of 254.9 metres, were identified and they yield a mean azimuth of 133.7^{o} ± 7.3^{o}.

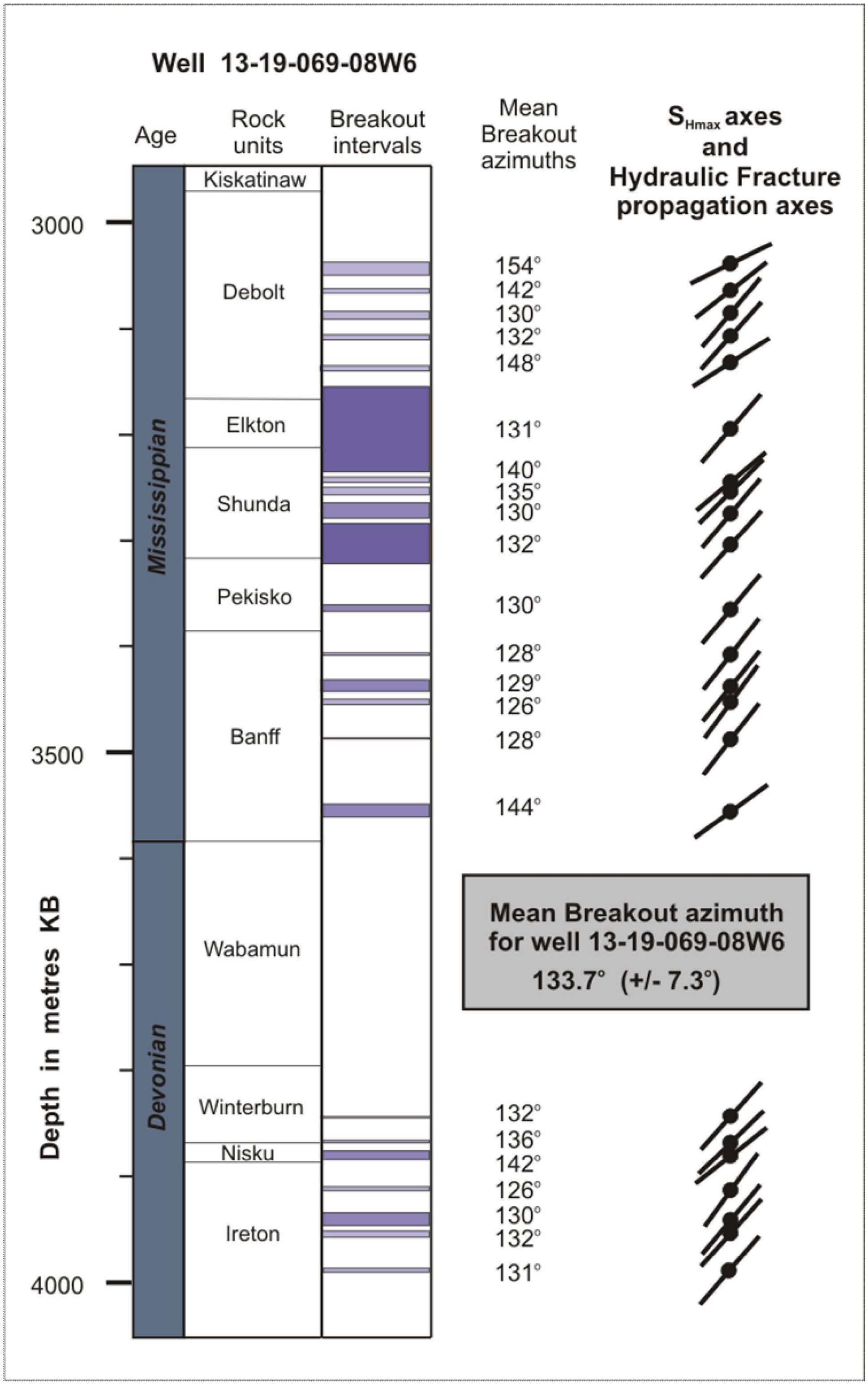


Figure 9.3. An example of the directional consistency of breakout long axes over depth that is typically observed in wells in the Western Canadian Sedimentary Basin. Propagation axes for hydraulic fractures are SW-NE.

Bell and others (1994) present maps of mean breakout axes for Mesozoic and for Paleozoic rocks in the WCSB. Although the distribution of the wells involved is not identical, there is no obvious difference in the directional signatures. The major breakout populations in wells in western Canada exhibit mean orientations that are approximately NW-SE, except around the Peace River Arch, where the axes trend more towards WNW-ESE. The same NW-SE signature is also apparent in three wells where breakouts were identified in the uppermost part of the Precambrian basement (Bell, 1996). Unpublished investigations, in which mean breakout axes were mapped for specific geological intervals, have confirmed this directional consistency with depth. Depth ranges at which breakouts were identified varied from well to well depending on what units exhibited breakouts, as well as on which intervals were logged with 4-arm dipmeters. Breakouts were most commonly developed in shales, limestones and dolostones, and were less frequently encountered in sandstones.

The mean axes of major breakout populations and of the other horizontal stress indicators are summarised in terms of stress trajectories in Figure 9.4. The shallowest breakout that supplied data for this map was logged at 113 m depth and the deepest at 5495 m. Figure 9.4 was created by drafting stress trajectories that respected the interpretations of local stress axes. The S_{Hmin} trajectories are aligned with the mean breakout population axes for wells closest to their path, and the S_{Hmax} trajectories are drawn at right angles to the S_{Hmin} trajectories. The map is believed to offer reliable principal stress axes for all ages of rocks in the basin, including the upper part of the Precambrian basement.

9.4 MEASURING PRINCIPAL STRESS MAGNITUDES

Stress magnitudes have to be measured or estimated, since there are no known natural phenomena that can record subsurface compressive forces with any precision. Here we examine both vertical and horizontal stress, and assess the controls they play on regional fracture systems.

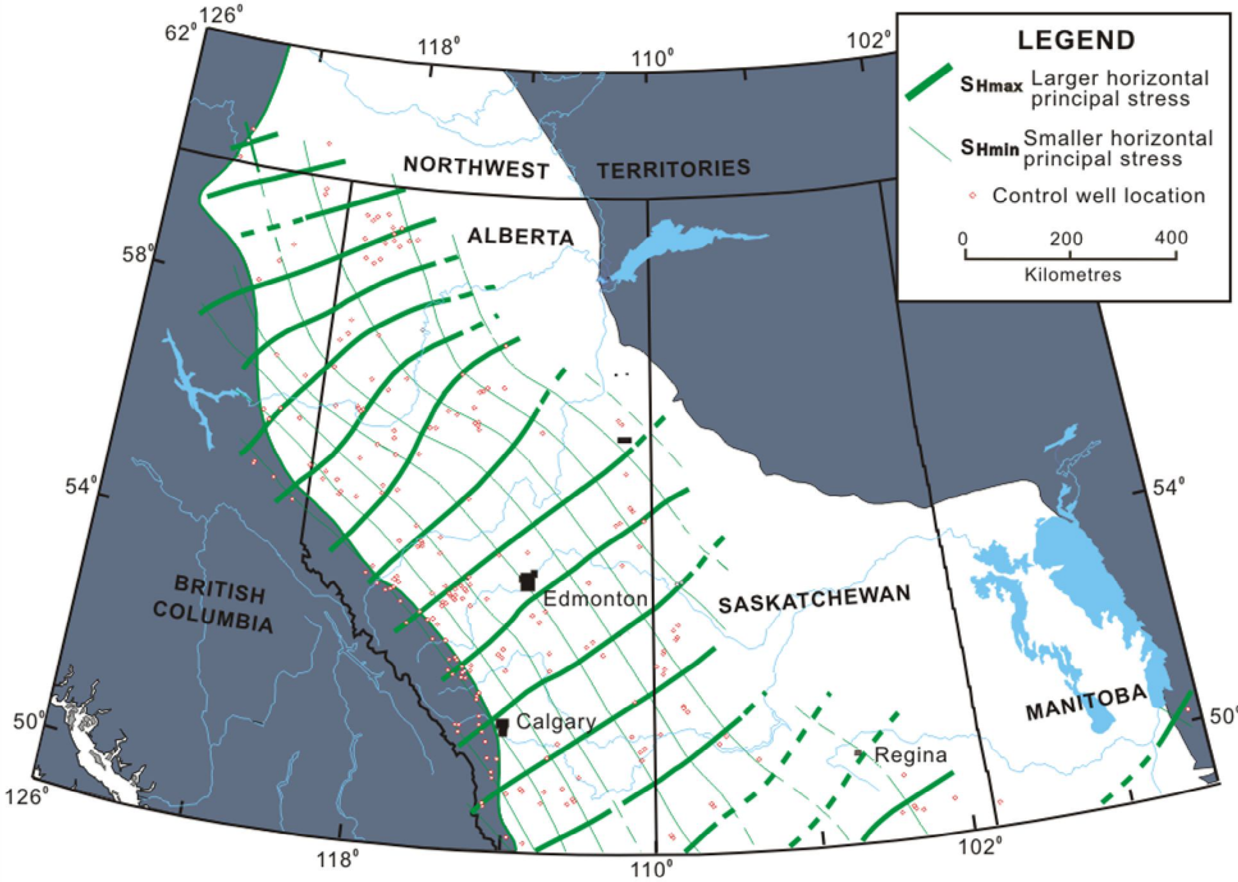


Figure 9.4. Horizontal stress trajectories in the Western Canadian Sedimentary Basin that are largely inferred from breakouts.

9.4.1 Vertical Stress

The vertical stress, S_V, at a point along the trajectory of a well is equivalent to the weight of the overburden, thus integrating the densities of all the overlying rocks will determine the load. Ideally, this is achieved using values from a density log that extends close to the surface and records little caving. Corrected densities can be extrapolated from adjacent uncaved intervals, or inferred from other logs and cuttings information, but the fewer corrections required the better. In most oil and gas wells, no logs are run before surface casing has been set, so there is an upper unlogged interval with no rock density information. However, the mean density for this interval can be obtained by linear extrapolation to the surface of the uppermost densities of the underlying logged interval (Fig. 9.5).

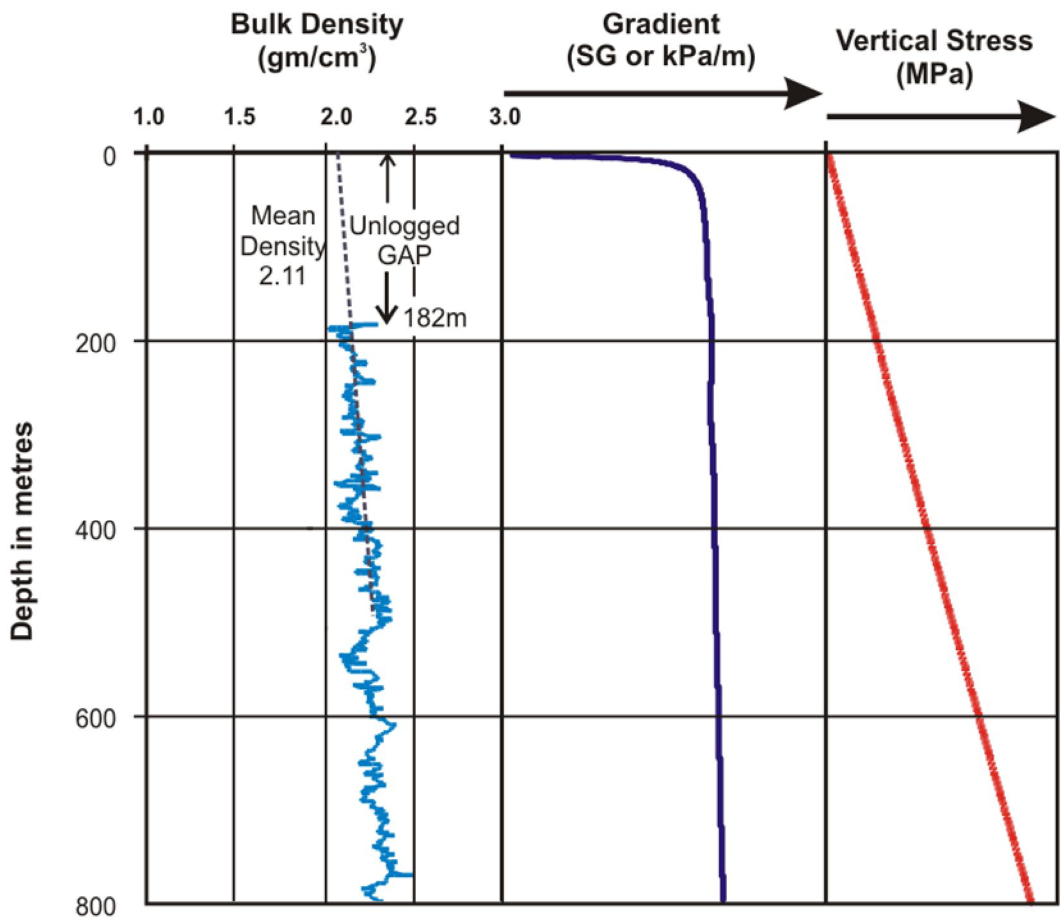


Figure 9.5. Vertical stress magnitudes are determined by integrating density logs. The mean densities of upper unlogged intervals are determined by extrapolating from deeper values.

The density logs used to estimate overburden loads on Alberta and northeastern British Columbia were selected considering: 1) the logged intervals commenced within a few hundred metres of the ground surface, 2) the logged intervals extended as deep as possible, 3) the wells exhibited minimal caving, and 4) logs are from wells that were close to vertical trajectories. Corrections were made for the caved intervals and the densities in the uppermost unlogged intervals were extrapolated from deeper log values. Cuttings descriptions were checked to ensure that lithological similarities existed between the unlogged intervals and the underlying sections that were extrapolated. In order to map lateral variations in vertical stress, density logs were selected from wells that were appropriately distributed geographically. True depths were used to calculate S_V magnitudes.

Figure 9.6 portrays estimated vertical stress magnitudes at 500 m depth with data drawn from density logs run in 91 wells. S_V magnitude increases towards the western margin of the basin, where denser rocks are present at shallower depths. The same configuration is portrayed on the S_V magnitude map for 1000 m depth (Fig. 9.7), although data coverage is less extensive to the east. The western increase in S_V magnitude, at the same depth, is interpreted as the result of these rocks having been more compressed over geologic time. Organic maturation levels (Nurkowski, 1994; Bustin, 1991) show that the rocks now exposed at the surface on the western side of the basin were originally buried beneath some 3-4 thousand metres of overburden that has since been eroded. This former load would have compressed these rocks and raised their densities more in the west than in the east where paleoburial was less.

9.4.2 Horizontal Stress

There are four main sources of data for estimations of horizontal stress: micro-fracturing, mini-fracture tests, leak-off tests, and fracture break-down. Figure 9.9 portrays all these processes in one diagram. In practice, mini-frac closure pressures yield essentially indistinguishable values, so it is reasonable here to interpret these also as accurate measures of S_{Hmin}. However, due to culling to remove tests from reservoirs that are not at virgin pressures, the mini-frac data set is not as large, or as areally distributed as desirable.

Leak-off tests (LOTs) are run below casing in open hole. Pressure on the drilling mud column is raised slowly until the pressure build-up ceases to be linear, at which point a small volume (less than 1 m^3) is believed to have begun to “leak-off” into the formation (Fig. 9.9). Near surface rocks often exhibit high tensile strengths and, therefore, generate leak-off pressures that are considerably higher than the stresses they are subjected to. For this reason, the majority of the LOTs selected for this study were run at depths greater than 300 m.

Fracture breakdown pressures are the pressures at which hydraulic fractures are initiated, when the rock surrounding the wellbore first breaks down as it absorbs an injected fluid during massive fracture treatment.

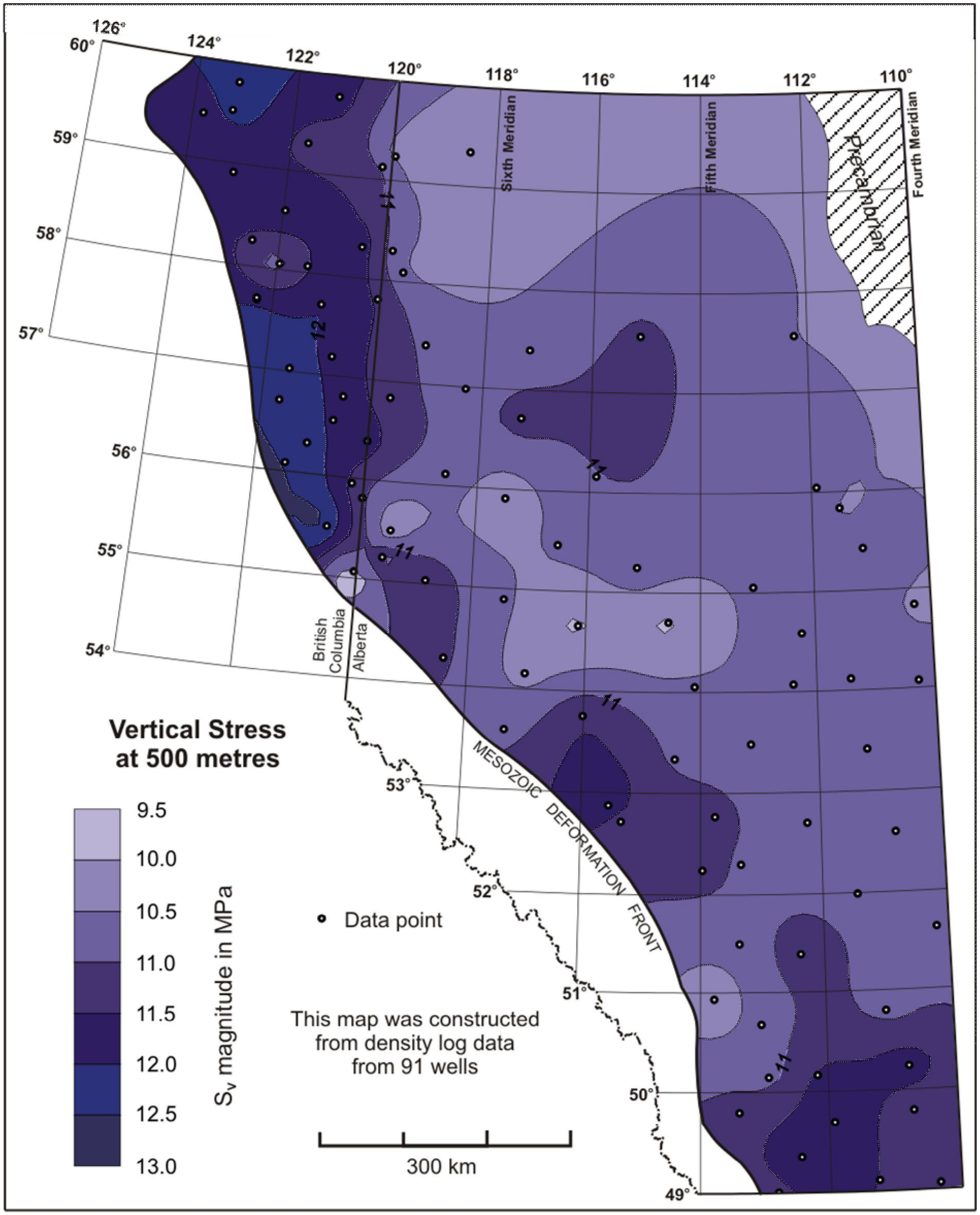


Figure 9.6. Vertical stress magnitudes at 500 m depth in the Western Canadian Sedimentary Basin contoured by kriging data from 91 wells.

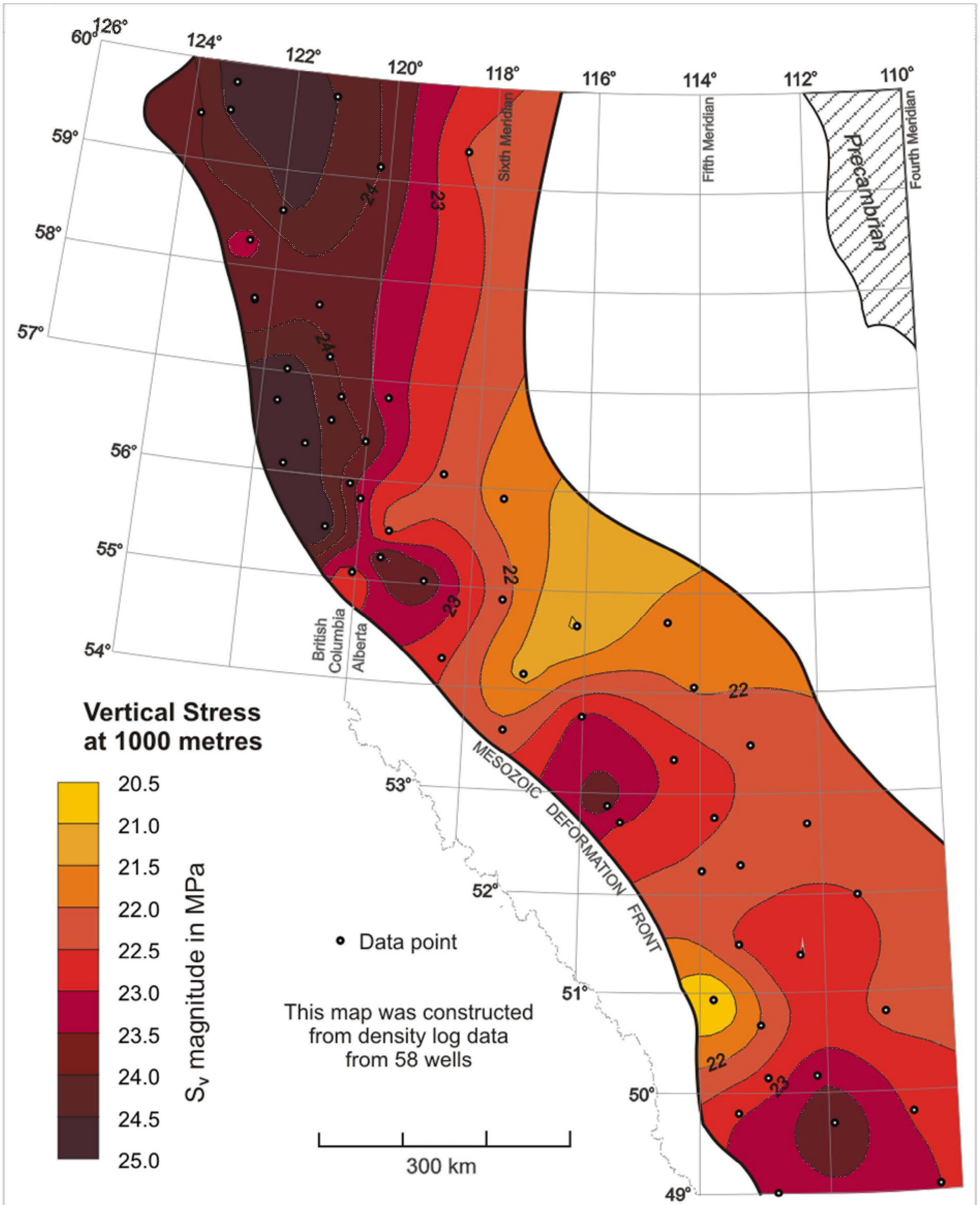


Figure 9.7. Vertical stress magnitudes at 1000 m depth in the Western Canadian Sedimentary Basin contoured by kriging data from 59 wells.

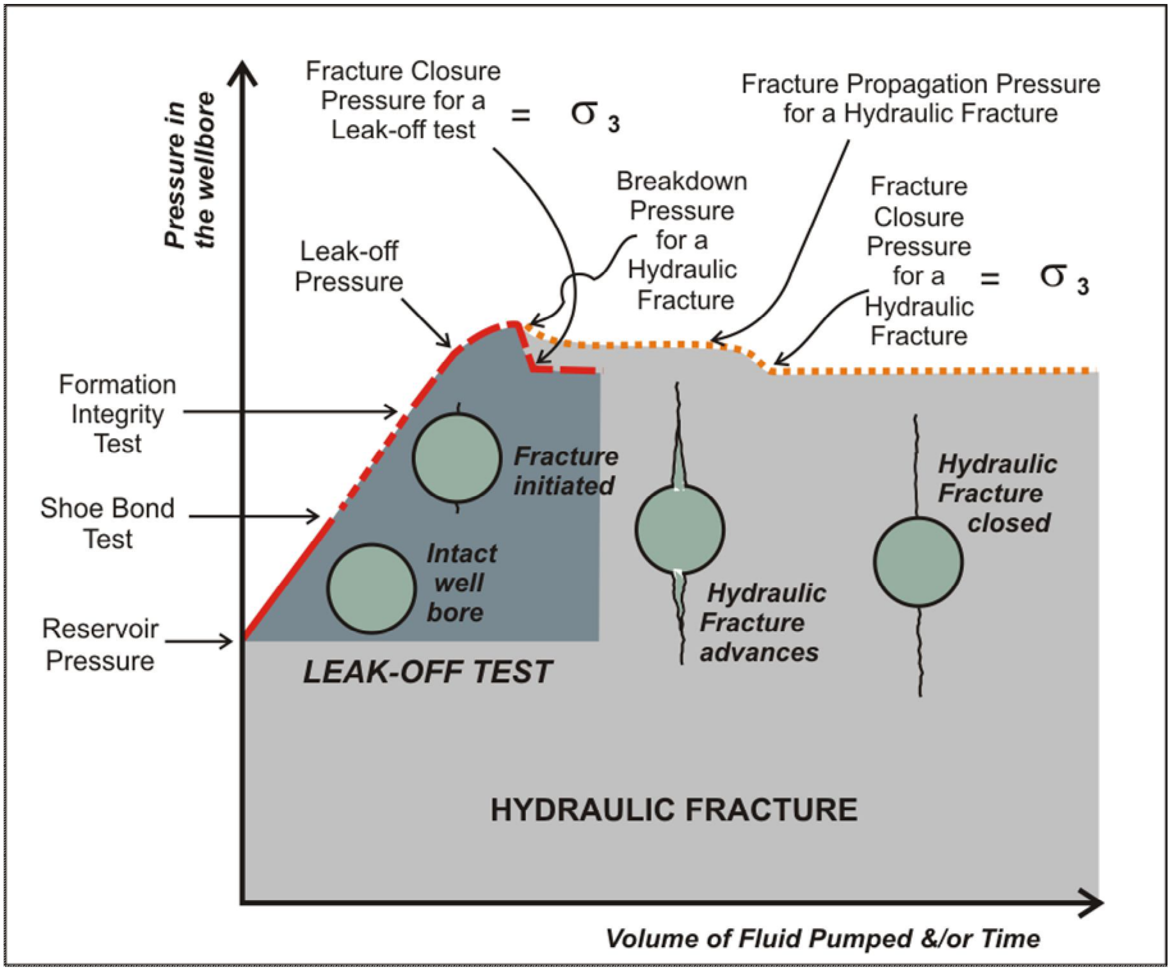


Figure 9.9. Schematic Pressure/Volume and Pressure/Time plot of the hydraulic fracture process showing how a leak-off test represents the early part of a full hydraulic fracture. Note that both the leak off pressure and the fracture breakdown pressure exceed the fracture closure pressure.

Strictly speaking, only closure pressures from micro-fractures will provide accurate measurements of the smallest principal stress, S_{Hmin}. There are relatively few such stress measurements in western Canada given the cost to run them. Initiating a fracture will always require more pressure than the minimum pressure required to keep it open (i.e. a closure pressure), so one can expect Leak-off tests (LOTs) and fracture breakdown pressures to be higher than the closure pressures derived from micro- and mini-fractures. Figure 9.9 suggests that leak-off will occur generally at slightly lower pressures than fracture breakdown, and that both will exceed fracture closure pressures. The latter conclusion is validated by the data presented here, but the former is not. In western Canada, the average leak-off pressures are actually greater than the average fracture breakdown pressures. Locally, in areas where deeper data were not available, such as in southeastern Alberta, the upper level for LOTs was set at 200 m.

All the micro-frac and mini-frac measurements of S_{Hmin}, and of the leak-off and fracture breakdown pressures from which this principal stress can be estimated, were made at specific depths in wells. In a few wells, as many as five pressures were measured at different depths (Fig. 9.9), but this was not common, thus detailed semi-continuous profiles of S_{Hmin} vs depth are not available. The only practical way in which maps can be generated is to treat these measurements as gradients. However, prior to doing so, some culling and data adjustments are required.

Anomalously high and low pressures have been reported for many LOTs and fracture breakdowns. Pressures yielding gradients less than 12 kPa/m were culled because they are close to hydrostatic gradients and imply that the permeability was good enough that no fracture was initiated. Gradients higher than 30 kPa/m were assumed to be related more to high tensile strength rather than in situ stress, as well as being significantly greater than any reasonable overburden loading (S_V gradient), so they too were culled.

Published information is available for 120 micro-frac and mini-frac measurements in Saskatchewan, Alberta and British Columbia range in gradient from 12.5 to 27.3 kPa/m (Bell et al., 1994; Hawkes and Hamid, 2009; McLellan, 1999; Woodland and Bell, 1999) with an average gradient of 19.4 kPa/m. For 947 selected leak-off tests (LOTs), gradients range from 13.3 to 30.0 kPa/m, with the average gradient being 23.2 kPa/m. There are 676 fracture breakdown pressures (FBPs) that yield gradients ranging between 12.2 and 30 kPa/m, with an average gradient of 19.3 kPa/m. If all these data sources are to be harnessed to map S_{Hmin} gradients areally, the gradients of the LOTs and fracture breakdown pressures need to be reduced so that they are compatible with the micro-frac and mini-frac gradients. Proportional reduction is one option; for example, reducing each leak off test gradient by 19.4/23.2. However, this procedure has the disadvantage of reducing the lower unculled gradients to less than 12 kPa/m, which is not a logical S_{Hmin} gradient. The approach taken here is to apply a graduated reduction whereby, if the gradient is 12.0 kPa/m, it is not reduced at all, whereas, if it is 30 kPa, it is reduced by a maximum amount. Graduated reduction has been undertaken so that the average gradients of the adjusted leak-off and fracture breakdown populations become 19.4 kPa/m. This was achieved by applying the following equations:

$$\text{Adjusted LOT gradient} = 12 + 0.57(\text{Original LOT gradient} - 12) \quad (9.1)$$

$$\text{Adjusted FBP gradient} = 12 + 0.99(\text{Original FBP gradient} - 12) \quad (9.2)$$

This approach yields S_{Hmin} gradients of reasonable magnitudes.

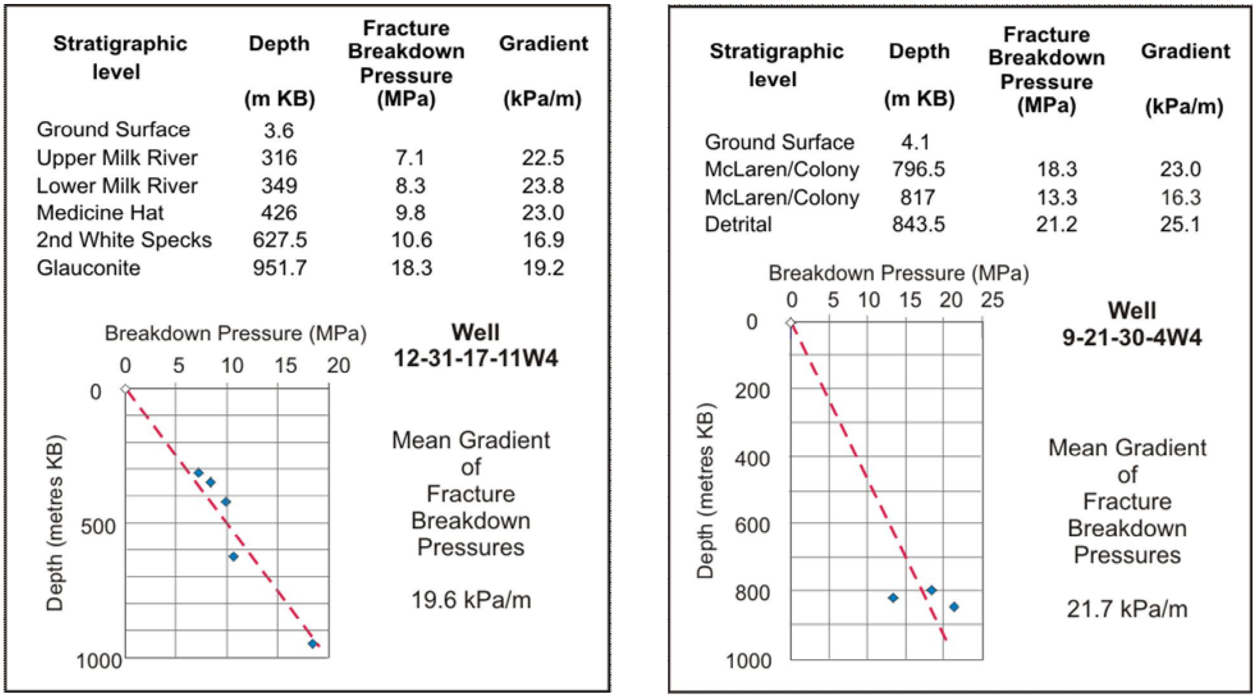
Currently no tools are available for measuring the larger horizontal principal stress, S_{Hmax}, at depth in wells. When this parameter has been required for borehole stability predictions, it has usually been estimated from an equation such as:

$$S_{Hmax} = 3S_{Hmin} - P_r - P_o \quad (9.3)$$

in which P_r is the fracture re-opening pressure and P_o is the pore fluid pressure (Bredehoeft et al., 1976). S_{Hmax} can also be determined by modelling breakout caving using various fracture criteria (Zhou, 1997).

If the Mohr-Coulomb fracture criterion is used, the following parameters are required: length of breakout long axis, length of breakout short axis, S_{Hmin}, S_V, formation pore pressure, drilling mud pressure, Poisson's ratio, original hole diameter, coefficient of friction and cohesive strength. The first six values are usually recorded in drilling records. Poisson's ratio can be set at 0.2-0.3 and the coefficient of friction at 0.6. Cohesive strength, however, is rarely known accurately and, unfortunately, the S_{Hmax} magnitude is strongly dependent on it. However, if the breakout is deep, then the rock's cohesive strength is likely to be low, and so one can arrive at a reasonable value for S_{Hmax}.

These models simulate failure under specific geomechanical circumstances and they assume that all the failed rock will have spalled away from the borehole wall. This is unlikely to occur soon after a breakout zone begins to develop. In North Sea wells, the most credible S_{Hmax} magnitudes were obtained from breakouts near the tops of drilled sections, where the walls of the wells had been open for several days and were subjected to considerable drill pipe abrasion, as well as the effects of tripping in and out when drill bits were changed (R. Bratli, personal communication, 1999).



Stratigraphic level	Depth (m KB)	Fracture Breakdown Pressure (MPa)	Gradient (kPa/m)
Ground Surface	3.6		
Upper Milk River	316	7.1	22.5
Lower Milk River	349	8.3	23.8
Medicine Hat	426	9.8	23.0
2nd White Specks	627.5	10.6	16.9
Glauconite	951.7	18.3	19.2

Stratigraphic level	Depth (m KB)	Fracture Breakdown Pressure (MPa)	Gradient (kPa/m)
Ground Surface	4.1		
McLaren/Colony	796.5	18.3	23.0
McLaren/Colony	817	13.3	16.3
Detrital	843.5	21.2	25.1

Figure 9.9. Examples of wells with multiple hydraulic fractures. In well 12-31-17-11W4, the hydraulic fractures were widely spaced stratigraphically and exhibited a series of fracture breakdown pressures that increased in magnitude with depth, allowing a reliable mean gradient to be calculated. In well 9-21-30-4W4, the hydraulic fractures were limited to a thin stratigraphic interval and exhibited variable fracture breakdown pressures, so that the mean gradient is poorly established.

9.4.3 Mapping S_{HMIN} Gradients

The unaltered micro-frac and mini-frac gradients, together with the adjusted LOTs gradients and adjusted fracture breakdown gradients, are mapped in kPa/m in Figure 9.11 using Kriging methodology. In Figure 9.10, the contours can also be regarded as representing S_{Hmin} magnitude values in MPa at 1000 m depth. Figure 9.11 portrays the distribution of the data points. The greatest cluster is concentrated along the western edge of the basin between latitudes 52° and 56°. The lateral variation in S_{Hmin} gradients across the basin is suggestive of two sets of lineaments, one semi-parallel with the Rocky Mountain deformation front and the other approximately perpendicular to it (Fig. 9.10). The latter lineament set is particularly interesting because it is aligned SW-NE in the northern and southern parts of the basin, but swings to SSW-NNE between latitudes 55 ° and 57 ° in approximately the same area where the S_{Hmax} stress trajectories are similarly deflected (Fig. 9.4). The implication is that horizontal stress orientation is in some way involved. It is possible that the “troughs” with the lower gradients contain rocks with denser open fracture networks than are found within the rocks in the adjacent higher gradient "ridges". All other factors being equal, the lower the S_{Hmin} magnitude the greater the permeability.

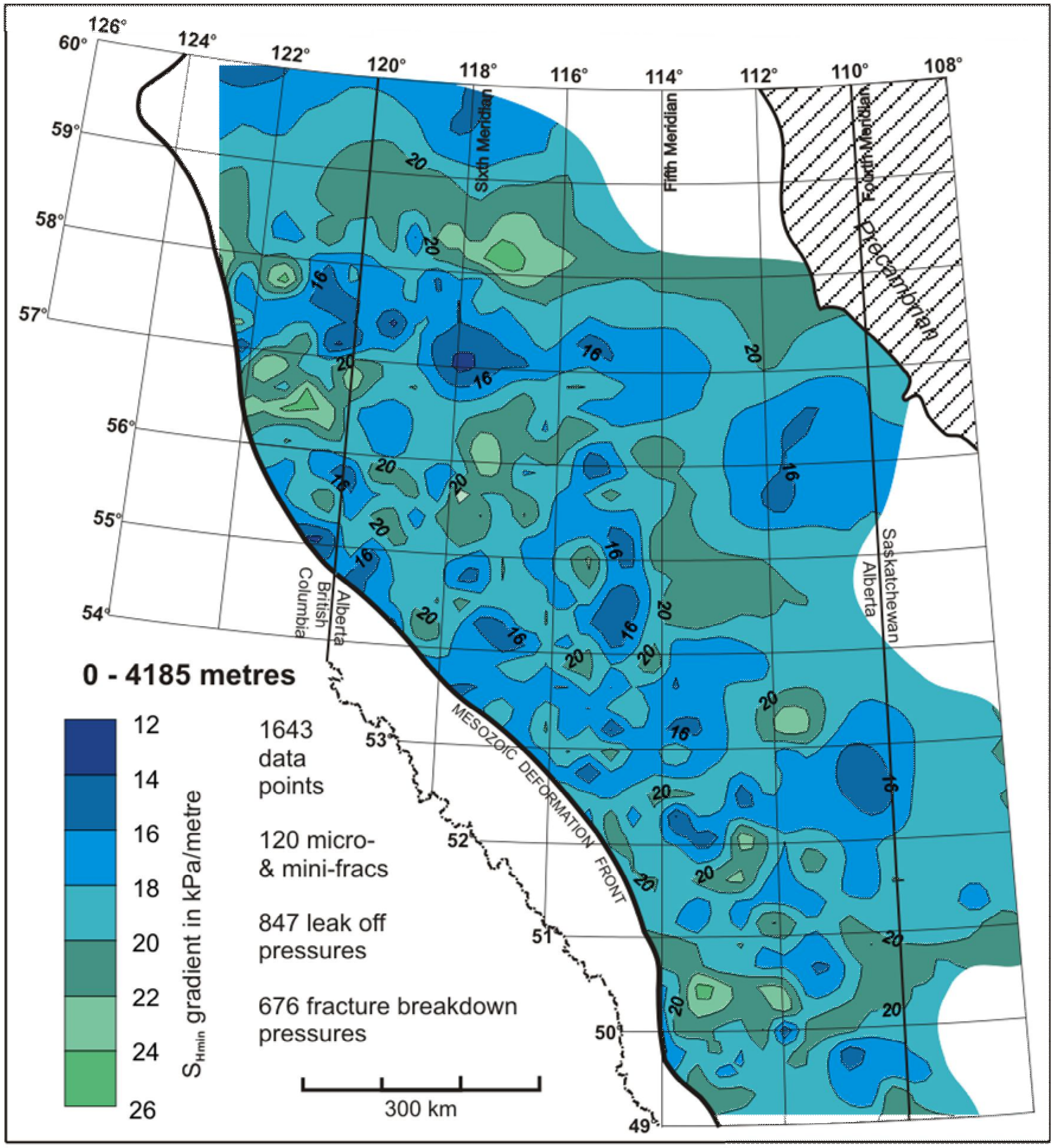


Figure 9.10. Map of inferred S_{Hmin} gradients across the Western Canadian Sedimentary Basin derived from micro-fracture and mini-fracture closure pressures, adjusted leak off test pressures and adjusted fracture breakdown pressures.

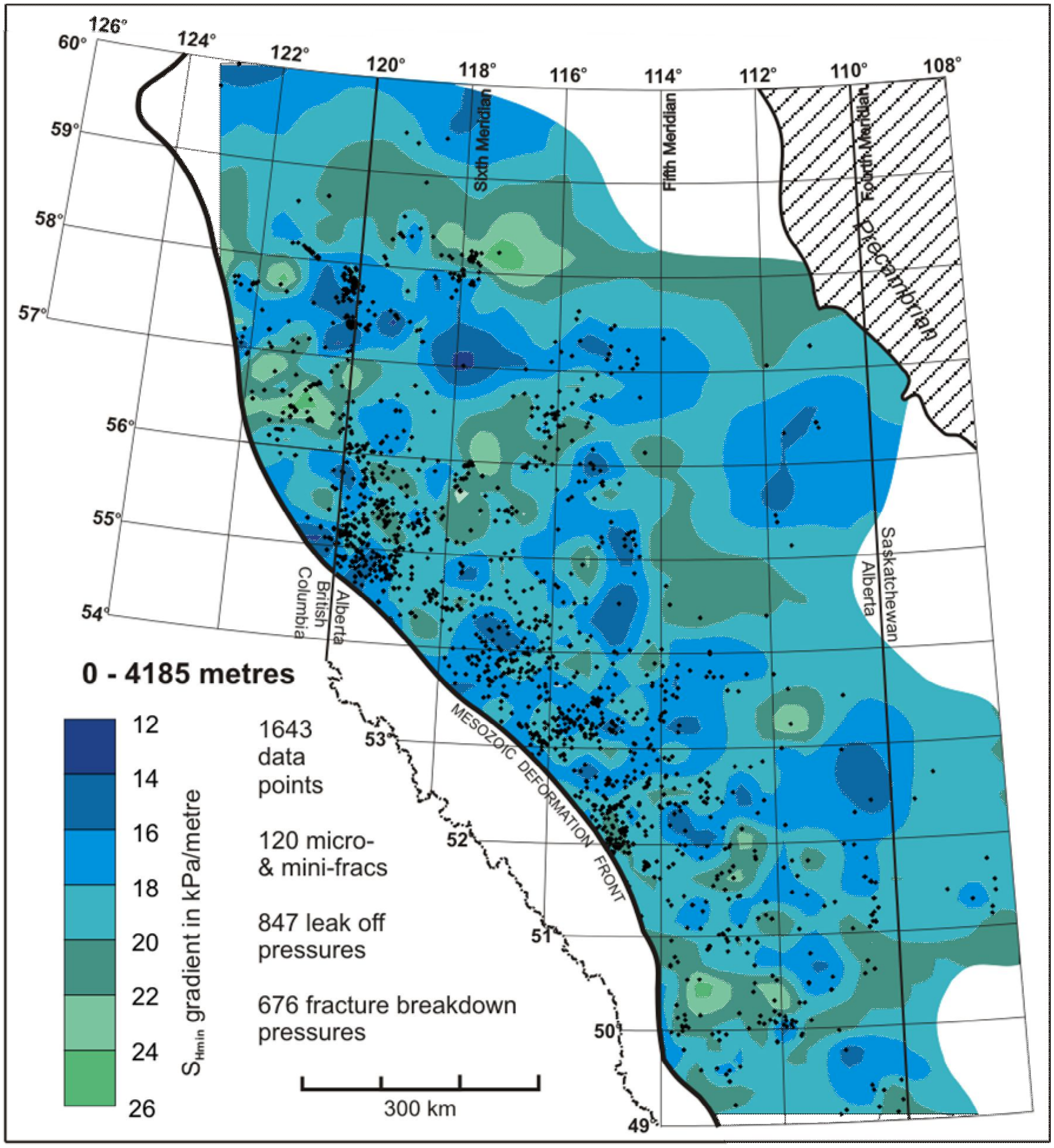


Figure 9.11. Locations of wells that supplied data for Figure 9.10.

Figure 9.10 represents the most comprehensive interpretation to date of lateral variations in S_{Hmin} gradients across the WCSB using data from public archives. The map could be refined considerably with the addition of more pre-fracture shut in pressures. Such interpretations and the pressure data that spawn them, however, are proprietary to the operating companies who commission hydraulic fracturing to enhance hydrocarbon production.

9.5 RELEVANCE TO GEOTHERMAL DEVELOPMENT

Exploitation of upper-crustal geothermal resources will require drilling wells and may involve hydraulically fracturing rocks. Figure 9.4 indicates the directions in which hydraulic fractures will propagate. They can be expected to be vertical and aligned with S_{Hmax} trajectories over most of the basin. Moreover, natural fractures that are aligned within ±20^{o} of the S_{Hmax} trajectories may be open to fluid transmission. Whether or not open fractures are present, it has been demonstrated that the optimal fluid flow axes in reservoirs will be aligned with S_{Hmax} (Heffer and Lean, 1991).

Locally, close to the Rocky Mountain Foothills (McLellan, 1999), and along the eastern fringe of the basin where the oil sands are being developed (summarised in Bell et al., 1994), S_{Hmin} magnitudes greater then S_V magnitudes have been reported. They suggest that horizontal fractures will propagate in these areas.

As noted earlier, S_{Hmax} trajectories are perpendicular to breakout long axes, and the breakout axes show consistent orientations in individual wells. Apart from the NNE-SSW trend over the area around the Peace River Arch, the main orientation of S_{Hmax} is NE-SW. It is not a local phenomenon restricted to western Canada. Zoback and Zoback (1990) have demonstrated that the WCSB lies in the northwestern part of the Mid-Continent Stress Province. In this province, NE-SW S_{Hmax} axes occur within an area bounded by the plains of the US Mid West, Arkansas, Tennessee, New York State, the Canadian Maritimes, the Arctic Islands (Cox, 1993) and the Northwest Territories (Gough et al., 1993). This consistent horizontal stress orientation over the whole mid-continent of North America is ascribed to northeastward flow in the underlying mantle that is pushing the North American plate northeastwards (Fordjor et al., 1993). In other words, the stress orientation signature in the WCSB is interpreted as a reflection of the absolute motion of the Earth's tectonic plates.

The magnitude of the smallest principal stress will determine what pressure will need to be applied in order to fracture subsurface rock units. Here, there is a choice as to what data are marshalled to provide appropriate insights. If the aim is to harness subsurface hot fluids for space heating and related applications it will be useful to consider data that were used to estimate S_{Hmin} at shallow depths.
Accordingly, Figure 9.12 portrays inferred S_{Hmin} gradients using only information from pressures measured between 156 m and 500 m depth. Data sources were: 5 micro-fracture closure pressure

gradients, 799 adjusted leak-off pressure gradients, and 56 adjusted fracture breakdown pressure gradients. The micro-fracture pressure data come only from shallow measurements in the Alberta oil sands located north of latitude 56° N and between longitudes 110° W and 112° W. The majority of the adjusted fracture breakdown pressure measurements are concentrated around latitude 59° N and longitude 119° W and are responsible for the high gradients mapped in that area. Because of the dominance of the adjusted leak off pressures, this map is quite similar to the S_{Hmin} gradient map (Fig. 9.10) that was generated from the entire data suite. The zones of higher gradients adjacent to the Mesozoic Mountain Front in southeastern British Columbia, shown on Figure 9.11, are not documented due to the limited shallow pressure data in this area. A further difference between the two maps is qualitative. The 156-500 m map does not exhibit quite the same degree of apparent NE-SW and NW-SE linear trends. However, the map does assemble and interpret the best available data for estimating likely fracture pressures for shallow geothermal projects and for identifying areas with possibly enhanced permeability.

It is interesting to compare this map to one generated from pressure measurements made between 500 and 1,000 m depth. Here the distribution of data sources is quite different. Only 16 micro- and mini-frac closure pressures are involved, plus a mere 30 adjusted leak-off pressure gradients, whereas there are 209 adjusted fracture breakdown pressure gradients measured in 196 wells (Fig. 9.13). Although the controlling data points are differently distributed, the 500-1,000 m map is compatible with the shallower 156-500 m map (Fig. 9.12). Common features include: a WSW-ENE trending high gradient region starting at latitude 50° N and longitude 114° W; a SW-NE trending high gradient ridge starting at latitude 52° N and longitude 115° W; a low gradient area centred around latitude 56° N and longitude 116° W, and a high gradient area around latitude 55° N and longitude 120° W.

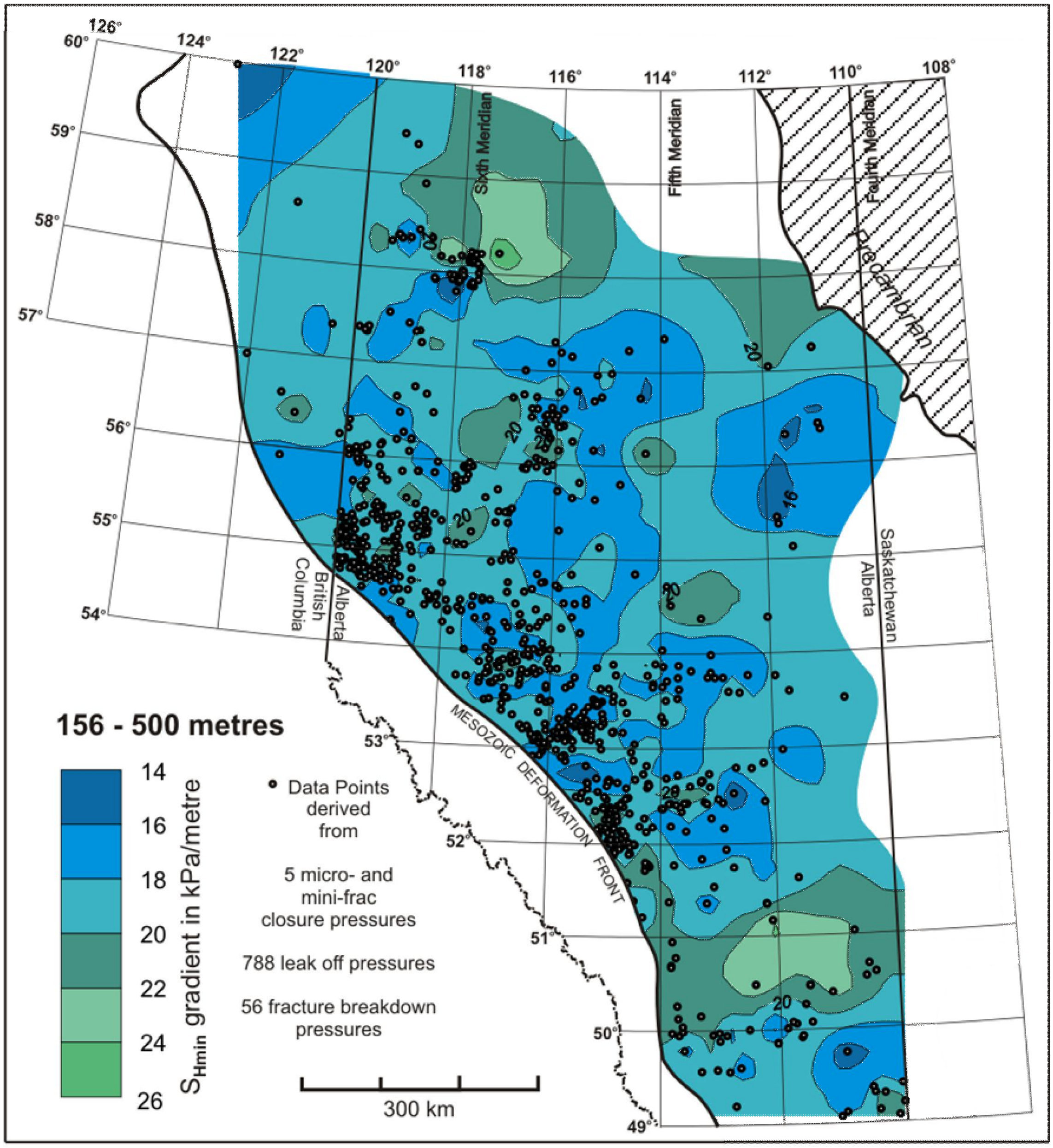


Figure 9.12. Map of inferred S_{Hmin} gradients across the Western Canadian Sedimentary Basin derived from micro-fracture and mini-fracture closure pressures, adjusted leak off test pressures and adjusted fracture breakdown pressures measured between depths of 156 m and 500 m.

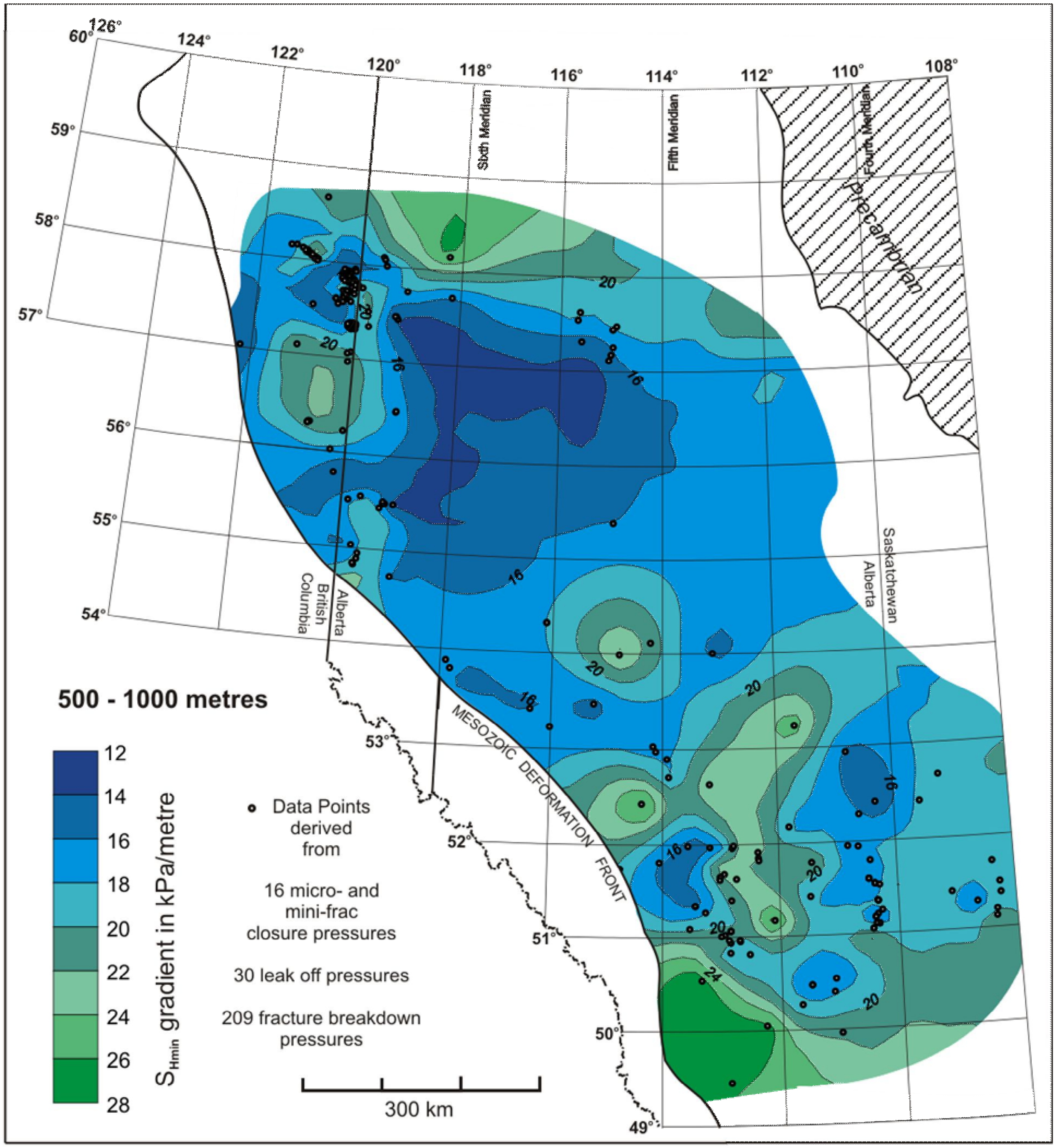


Figure 9.13. Map of inferred S_{Hmin} gradients across the Western Canadian Sedimentary Basin derived from micro-fracture and mini-fracture closure pressures, adjusted leak off test pressures and adjusted fracture breakdown pressures measured between depths of 500 m and 1000 m.

Development of future geothermal resources for power generation in western Canada is likely to involve deep drilling into the Precambrian basement rocks (Tester et al. 2006; Lund, 2007; Majorowicz and Grasby, 2010a; 2010b). Publicly available information on horizontal stress magnitudes at deeper levels comes largely from hydraulic fracturing that was performed to enhance hydrocarbon production rates from oil and gas reservoirs. No measurements have been reported for Precambrian rocks. However, there are over 500 applicable pressures that were measured between 1,000 and 4,195 metres depth. These consist of 97 micro-fracture and mini-fracture measurements, 29 adjusted leak off pressures and 409 adjusted fracture breakdown pressures. Figure 9.14 portrays the estimated S_{Hmin} gradients derived from these measurements.

South of Latitude 55° N, this map is quite similar to the Figure 9.10 and is reasonably compatible with the 156-500 m map (Fig. 9.12). North of 55° N, however, differences are apparent particularly when Figure 9.14 is compared to Figure 9.10. Figure 9.14 shows a high gradient ridge complex that runs SW-NE from latitude 55° N and longitude 120° W. There is some indication of such a feature on Figure 9.10, but it is not pronounced. Figure 9.13 lacks data over that region, so no comparisons can be made. Significantly, the high S_{Hmin} gradient ridge complex shown on the map of estimated S_{Hmin} gradients measured below 1,000 m depth corresponds areally approximately with the Peace River Arch (Grayston et al., 1964). This, in turn, suggests that the horizontal stress magnitudes are higher at constant depths because of the elevated Precambrian basement.

For geothermal powered electrical generation, recovered fluids will need to reach temperatures of more than 150 °C. Such temperatures are found within Precambrian rocks along the western edge of the WCSB (Bachu and Burwash, 1994), although it may require drilling deeper than 6,000 m to reach 150 °C (Grasby et al., 2009, Majorowicz and Grasby, 2010b). Figure 9.15a compiles the deepest data available for this study for estimating S_{Hmin} gradients. Contoured are S_{Hmin} gradients inferred from measurements made between 2,000 and 4,195 m depth. Figure 9.15b shows where temperatures greater than 150 °C are present at the top of Precambrian rocks (Bachu and Burwash, 1994). As can be seen, the inferred gradients range from 14 to19 kPa/m over the areas where the temperatures are highest. This argues well for hydraulic fracturing and also for possibly encountering some open fractures. The high S_{Hmin} gradients encountered over the Peace River Arch shown in Figure 5.15 were largely derived from hydraulic fracture treatments conducted at depths between 1,000 and 2,000 m, and do not seem to characterise the deeper rocks.

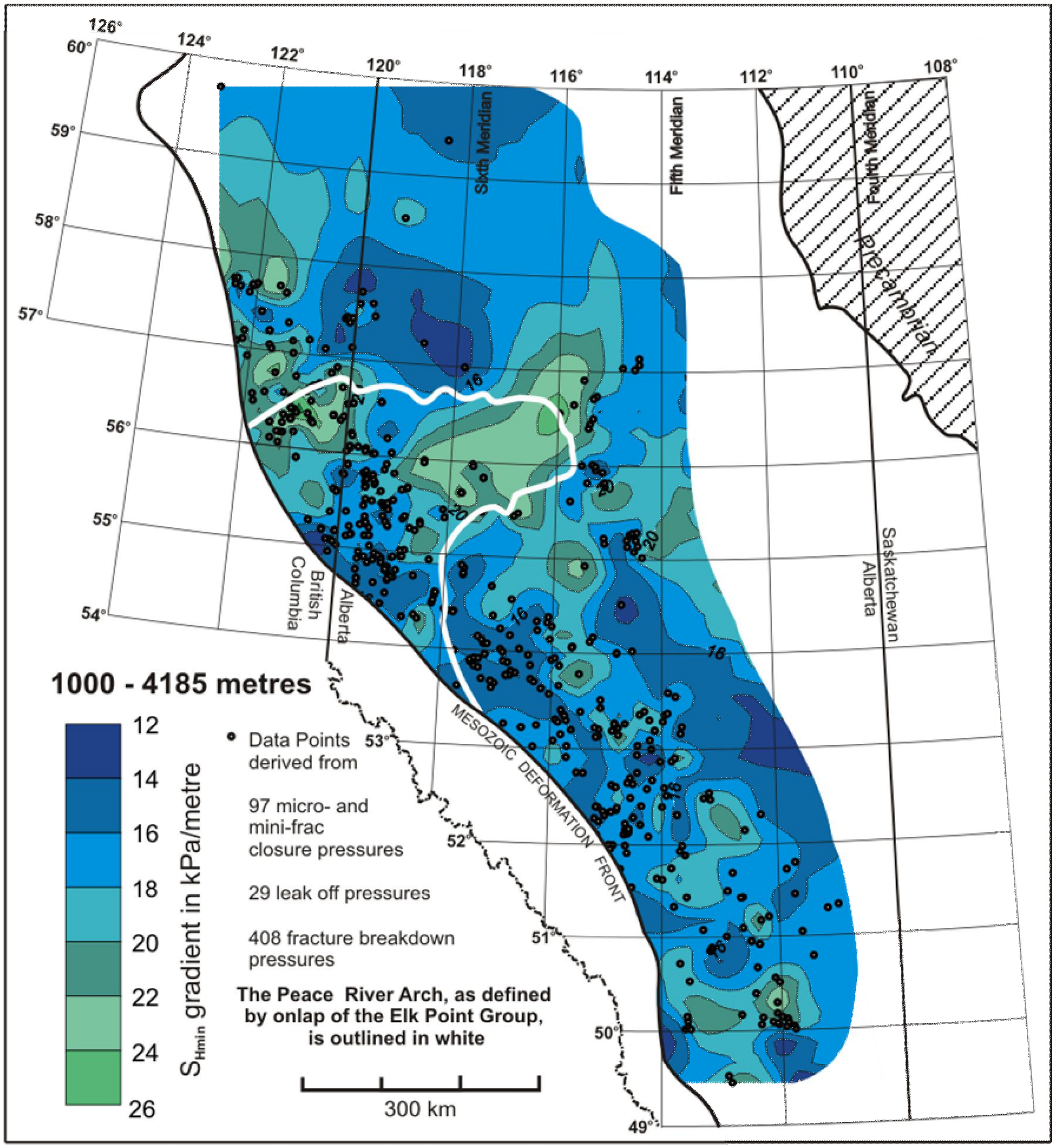


Figure 9.14. Map of inferred S_{Hmin} gradients across the Western Canadian Sedimentary Basin derived from micro-fracture and mini-fracture closure pressures, adjusted leak off test pressures and adjusted fracture breakdown pressures measured between depths of 1,000 m and 4,195 m.

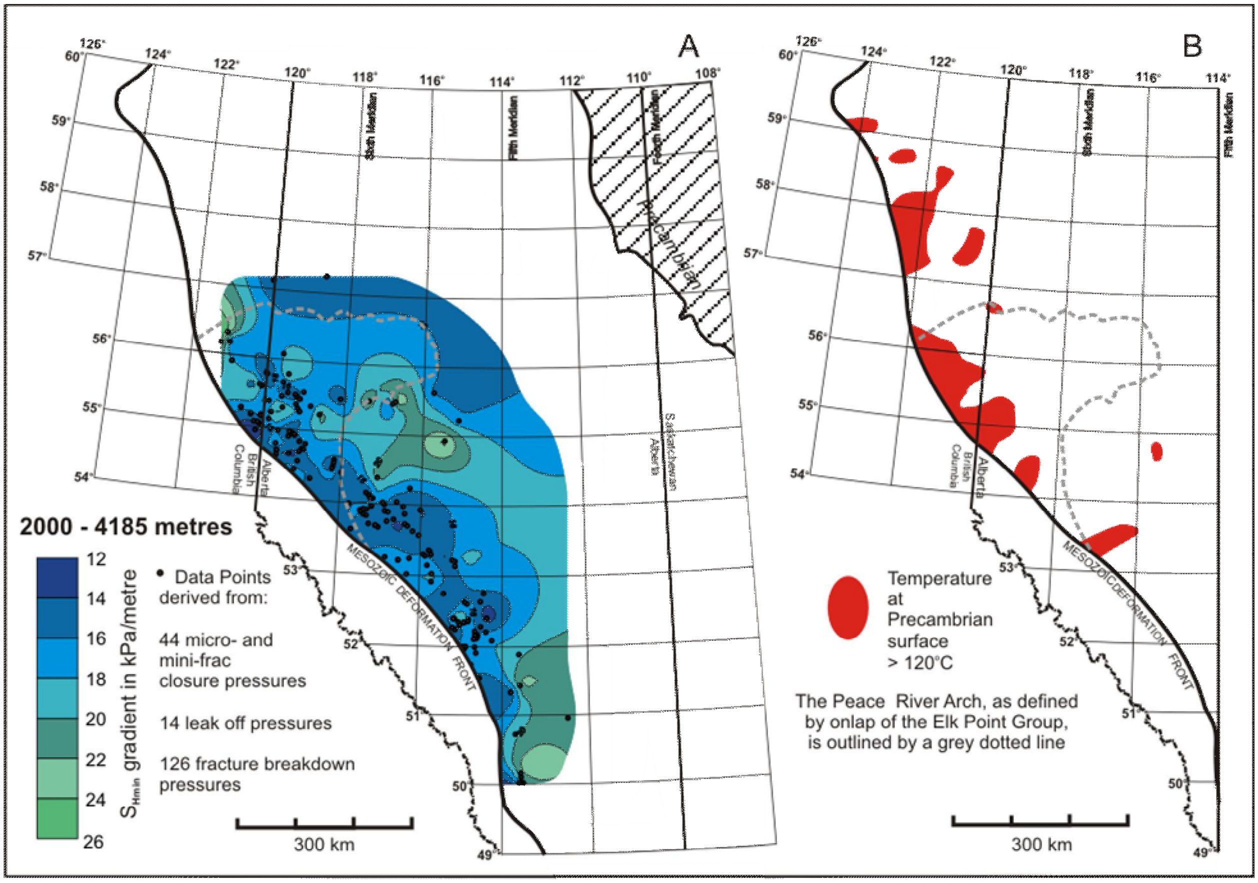


Figure 9.15. a) Map of inferred S_{Hmin} gradients across the Western Canadian Sedimentary Basin based on pressures measured between depths of 2,000 m and 4,195 m. b) Areas where the temperature at the top of the Precambrian basement exceeds 120°C (after Bachu and Burwash, 1994).

9.6 CONCLUSIONS

This study predicts the propagation axes of subsurface hydraulic fractures will be SW-NE, except over the Peace River Arch area, where they will trend more towards SSW-NNE. At constant depth, vertical stresses increase towards the Rocky Mountain front. The smallest principal stress is horizontal over most of the Western Canadian Sedimentary Basin and it varies in magnitude across the region. There are suggestions of low stress lineaments oriented similarly to the stress trajectories. These apparent lineaments may be diagnostic of increased abundance of natural fractures and enhanced permeability.

The greatest benefits of this compilation will be for those geothermal projects that involve shallow drilling. Unfortunately, few stress orientations and magnitudes have been measured at the depths that will probably need to be drilled for geothermally-powered electrical generation. Clearly, acquiring such data will be beneficial, but the costs will be considerable.

The stress magnitude maps can be enhanced with additional data. Innumerable density logs are publicly available if detailed vertical stress maps are required. A considerable body of additional information on smaller horizontal stress magnitudes can be derived from hydraulic fracture records. However, much of this information is held by the operating companies and would need to be released. These hydraulic fracture records would not extend significantly the depth of coverage of the S_{Hmin} gradient maps presented here, but they would refine their accuracy. In areas where a large amount of hydraulic fracturing was undertaken in specific rock units, it would be possible to prepare well-constrained S_{Hmin} magnitude maps for those stratigraphic levels. It would be especially worthwhile to utilise this type of information in areas where deep geothermal development is being considered.

S_{Hmin} gradients always can be used to generate maps at specific depths or selected stratigraphic horizons (Bell and Bachu, 2004). In practice, many of the measurements are likely to come from significantly different levels, so this will limit the accuracy of such maps. However, it is a first step and can be used to high-grade areas for future development.

10. ENVIRONMENTAL IMPACTS

10.1 INTRODUCTION

When developed and managed correctly, geothermal energy may be considered a renewable energy resource. If improperly managed however, geothermal developments may result in adverse affects including: alteration of groundwater chemistry, the addition or removal of heat from groundwater dependent ecosystems, and changes in groundwater flow patterns. In some large-scale high temperature systems additional potential impacts include: habitat disturbance, erosion, seismicity, noise, and the release of pollutant emissions. Geothermal energy can be part of the solution to the reduction of greenhouse gas emissions, and development of a secure renewable energy supply. However, like any other energy resource it must be developed in a thoughtful manner to ensure that there are minimal environmental impacts.

In order to provide a better understanding of the potential environmental impacts of geothermal energy and to ensure responsible exploitation of this resource, environmental impacts for both direct-use (low-temperature and medium temperature systems) and electrical generating applications (high-temperature systems) are examined in this chapter.

10.2 DIRECT USE

Over the last few decades, low-temperature geothermal systems have played a vital role in the growth of geothermal energy use in residential homes, small commercial buildings, agriculture and aquaculture. Low-temperature geothermal systems can be exploited to heat and cool homes with respect to the season by use of ground-source heat pumps. This fairly new technology allows virtually anyone in the world to exploit geothermal resources (WEC, 2007). While direct-use applications have been used extensively in Canada, some potential environmental concerns have been addressed regarding the effects of these applications on shallow groundwater systems, groundwater flow and source water protection.

10.2.1 Shallow Groundwater Systems

There has been an abundance of attention given to the risk of groundwater contamination from geothermal systems, both high- and low-temperature. Primary problems related to groundwater chemistry in low-temperature geothermal systems include: 1) the precipitation of minerals such as calcium carbonate, and iron and manganese oxides, which result in the scaling of heat exchangers and clogging of wells; 2) the corrosion of piping and heat exchangers by ambient and heated groundwater; 3) biofouling of the well intake area; and 4) the clogging of the aquifer as a result of precipitation of minerals within the aquifer or the transport of precipitates into the aquifer. Most of these problems result in a lowering of the system efficiency rather than causing a negative environmental impact.

Changes in groundwater chemistry due to temperature-dependent geochemical reactions have been noted in several shallow heat tracer experiments (e.g. Palmer and Cherry, 1984; Perlinger et al., 1987) and in some operating low-temperature geothermal systems (van Loon and van der Heide, 1992). This has been dealt with from a system sustainability perspective in terms of well clogging in open loop systems, but not in the larger hydrogeologic system. Results from a study at the University of Minnesota in the 1980s (Perlinger et al., 1987) suggested that precipitation of minerals, usually carbonates, near the well was accompanied by dissolution and enhancement of permeability further away from the well as the temperature of those waters created undersaturated conditions for the same minerals. This idea is also supported by a modelling exercise carried out with PHREEQC by Ferguson and Underwood (2006).

Biofouling of well screens can be particularly problematic in low-temperature geothermal systems, particularly where manganese and iron are present at moderate to high concentrations in the natural aquifer (e.g. Bridger and Allen, in press). Biofouling gradually reduces the efficiency of pumping through progressive buildup of slime on the well screen. However, biofouling is not restricted to geothermal systems, but is a pervasive problem in many pumping systems. Treatment technologies continue to improve.

10.2.2 Source Water Protection

One of the prime concerns voiced respecting low-temperature geothermal systems has been the risk of interconnecting naturally hydraulically-separated geological formations, which is a general concern in source water protection (e.g. Santi et al., 2006); this has been characterized as a specific risk for injection of spent geothermal waters (Arnold, 1984). Cross-contamination of aquifers has been addressed in many well construction guidelines and is addressed in the Water Acts of many jurisdictions in Canada, although often indirectly. In some jurisdictions, such as New Brunswick, closed-loop heat pumps are illegal within source-water protection zones (*Clean Water Act*, N.B. Reg. 2000-47). Guidelines by the National Ground Water Association (McCray, 1997) and the International Ground Source Heat Pump Association (Skouby, 2008) for closed-loop heat pump systems also address this issue.

One issue raised respecting low-temperature systems is the potential for contamination of groundwater by the potential leakage of various fluids used in closed-loop heat pumps. Klotzbucher et al. (2007) examined the fate of ethylene and propylene glycol, the most commonly used heat exchanger fluids, in groundwater. Both chemicals were found to be readily biodegradable under both oxic and anoxic conditions. However, anti-corrosion inhibitors and biocides, commonly found in heat exchanger fluids, were found to inhibit biodegradation of glycol. Additionally, some of these additives are toxic and persistent in subsurface environments.

10.2.3 Groundwater Flow

Open-loop heat pumps are generally considered to be sustainable from a water resources perspective because the vast majority of systems are non-consumptive. This view, based on the water budget of an aquifer, does not guarantee that negative impacts will not occur. In a series of papers on water resources, Bredehoeft et al. (1982) and Bredehoeft (2002) make compelling arguments that sustainable development of an aquifer cannot be assessed from a large-scale water budget. Consideration of the local effects of well hydraulics indicates that there is the possibility of affecting groundwater flow locally (Ferguson and Woodbury, 2007; Younger, 2008). This is particularly true if there is significant background groundwater flow, which would allow for migration of plumes of water with temperatures different from background levels away from production wells (Banks, 2009). Such migration effects are a particular problem where closed-loop geothermal or borehole systems are installed in aquifers of moderate permeability. Because there are no hydrodynamic controls on the system, injected heat will simply migrate away from the borehole field. In open-loop systems, hydrodynamic control of the well field is possible through careful placement and operation of wells (Allen, 1997; Allen et al., 2000).

Excessive production withdrawal, which occurs when reinjection is not carried out, such as pump-and-dump systems, can lower the water table and create temperature and pressure gradients within the groundwater reservoir (Ferguson and Woodbury, 2006). Altering such groundwater movement can have significant impacts on groundwater-surface water recharge and discharge processes (Ferguson and Woodbury, 2007). This could have profound effects on groundwater users in the immediate vicinity, and could also have an effect on groundwater-surface water interaction. For this reason, groundwater extraction should be accompanied by reinjection in most cases. Investigation of potential impacts on other groundwater users and ecosystems should also be considered in a similar manner to consumptive groundwater extraction.

Interference between low-temperature geothermal energy systems has not yet been identified as a major problem in Canada, despite the growing number of system installations and lack of regulation in most jurisdictions. Some problems have been observed in Canada however (e.g. Ferguson and Woodbury, 2006) and elsewhere (e.g. Malmo, Sweden; Andersson and Sellberg, 1992). The rapid growth in the number of these systems has also created concern that interference will become unavoidable in the future (Fry, 2009). The common problem is thermal breakthrough between wells, which results when the water that is being injected into the aquifer makes its way to an extraction well and thereby "contaminates" the temperature of the water being withdrawn. The potential for thermal breakthrough depends on the spacing of the production wells, the regional groundwater flow velocity and direction, and the presence of preferential flowpaths (Jenne et al., 1992). Typically, thermal breakthrough occurs if the wells are placed too close together and is exacerbated by large cones of depression and high flow velocities between pumping and injection wells (Michel and Allen, 1997). An interspersed well system that is designed with careful consideration of aquifer thickness, heterogeneity and well production rate can limit the occurrence of thermal breakthrough (Michel and Allen, 1997). These particular issues can be resolved or managed if sufficient and optimal spacing between wells is maintained (Ferguson and Woodbury, 2006). However, it should be noted that legislation to impose such management is currently poorly developed (Haehnlein et al., 2010).

10.2.4 Benefits and Recommendations

Many of these problems are avoidable if consideration of the potential for geochemistry problems is considered in advance of the system design phase. Many design strategies and numerous water treatment technologies have been used to mitigate these problems (e.g. Jenne et al., 1992). Several researchers have made significant advances in providing solutions to corrosion and scaling problems (e.g. Koch and Ruck, 1992) and some have developed computer software to examine the hydrogeochemistry of aquifers used for low temperature geothermal systems (e.g. Jenne et al., 1994). Grouting and pipe specifications are given in many guidelines including those from the Canadian Standards Association (CSA, 2002), the International Ground Source Heat Pump Association (Skouby, 2008), and the National Ground Water Association (McCray, 1997) and it appears that this issue has not been a large problem given the number of these systems operated in Canada versus the small number of reported incidents.

10.3 ELECTRICAL GENERATION

Geothermal power plants, developed for the purpose of producing electricity, will have similar environmental impacts as direct-use applications but at a much larger scale. Along with scale, the technologies used and the ecological region at which the facility is located will also determine the level of environmental impacts. These potential impacts will be at varying levels of concern throughout exploration, production testing, construction and operation; not only affecting the environment but any persons or wildlife working or living in the surrounding region.

10.3.1 Land Use and Habitat Disturbance

While the majority of geothermal developments have been limited to tectonically active zones, newer technologies for geothermal resource extraction have increased opportunities for geothermal development in a wide range of geographic regions and ecosystems. Habitat disturbance and the impacts of geothermal development on wildlife and vegetation will need to be investigated and continuously monitored throughout all phases of development with consequences of developing in remote or pristine areas, areas of cultural and archaeological worth, and areas of high economic value, carefully evaluated.

Geothermal environments offer some very unique biological, chemical, and geological conditions that create rare ecosystem (Boothroyd, 2008; Burns and Leathwick, 1995, Grasby and Lepitzki, 2002). Some ecologically sensitive and rare species which have already been identified in Canada's geothermal habitats, include the Banff springs snail (*physell johnsoni*), the southern maidenhair Fern (*Adiantum capillus-veneris*), the Nahanni aster (*Symphyotrichum nahanniense*), and the Vivid Dancer damselfly (*Argia vivida*). These particular species have been identified as indigenous to thermal springs in Banff, Fairmont, Meager Creek and Nahanni and are either protected by COSEWIC (Committee on the Status of Endangered Wildlife in Canada) or SARA (Species At Risk Act). Classified as "endangered" or "at risk", these species face the risk of extirpation with even small disturbances to their habitat. As suggested by Bromley (2003) and cited by Boothroyd (2008), the principal aim of geothermal systems management should be to encourage integrated use of resources while protecting the diversity of thermal features in a region. Furthermore, he suggests that designating protection (from development) to several key geothermal systems (rather than individual features) may help to achieve such goals provided there is mitigation for any unavoidable and adverse changes to surface features (e.g. introduction of foreign bacteria or slight changes in temperature). Mitigation measures that can be used to minimize possible threats to thermal habitats include waste water reinjection back into subsurface reservoirs, restricting development within key geothermal habitats, and having an in-depth knowledge of site characteristics. These mitigation strategies proved to be helpful in reintroducing populations of Banff snails to the Upper Middle and Kidney springs on Sulphur Mountain, where populations had previously been extirpated as a result of human disturbances (Parks Canada, 2009). Clearly, although thermal springs are a useful exploration tool, there is a need to ensure any developments near thermal spring outlets maintain spring flow in order to protect unique ecosystems.

Environmental impacts associated with geothermal exploitation are, for the most part, limited to the area directly surrounding the developed site (Andersen, 1975). The actual amount of surface area disturbed by geothermal development can vary from 10 to 50 % of the total area of development (including land occupied by pipelines and wells) and is primarily a function of the facilities' electrical capabilities (Chorney and Sherwood, 1981). As the generating capacity of a geothermal plant increases, the number of production wells, roads, transmission lines, and pipelines will also increase (Chorney and

Sherwood, 1981). Distribution of wells is most often dependent on the location of the heat reservoir and properties of the steam or water. However, geothermal sites under rapid development tend to develop wells in closer proximity to one another, resulting in higher well density; while sites developed more slowly tend to have wells spaced further apart, requiring not only more land but longer pipelines (US EPA, 1977). Advanced directional (slant) drilling or slimhole drilling technology has evolved in such a way that these impacts may be minimized. Using slant drilling technology, several wells can be drilled from one location, thus reducing the amount of land needed for drilling pads, access roads, and geothermal fluid piping. Slim-hole wells, on the other hand, are only 4-6 inches in diameter while traditional geothermal exploration wells have been 8-12 inches in diameter. Slim-hole drilling also reduces the amount of land needed for site preparation and road construction. This relies, however, on new technology that allows narrower pump design to maintain production volumes from narrower boreholes.

Despite the environmental advantages of other renewable energies, the average land use requirements for geothermal development are substantially lower than solar or wind (Fig. 10.1). In comparison with other fossil fuels, geothermal facilities require 1-8 acres per MW of production capacity, whereas nuclear and coal plant operations require 5-10 acres per MW and 19 acres per MW of land, respectively (DOE, 2009). With appropriate planning and management of well spacing and plant design, land use requirements for geothermal development can be minimized even further.

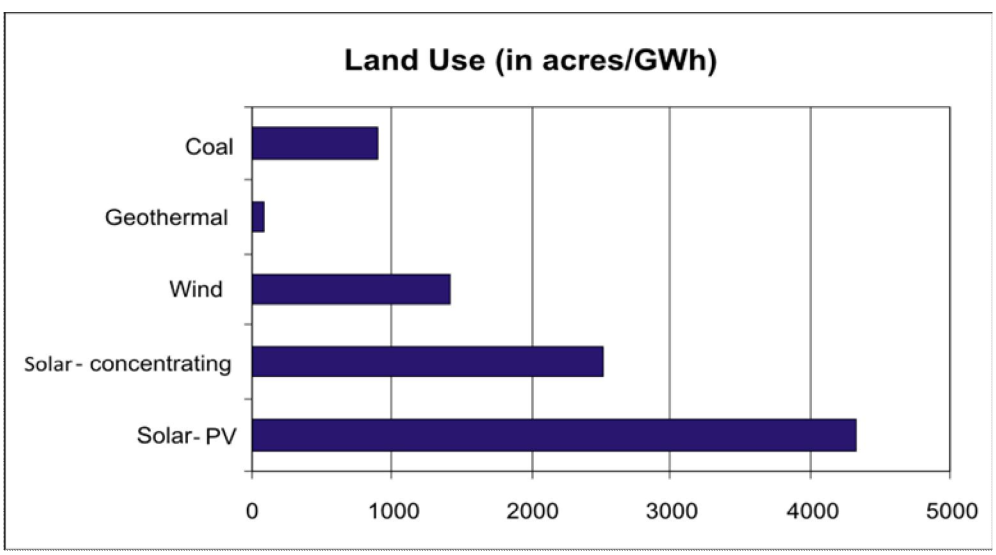


Figure 10.1. Average land use requirements for various renewable energies and coal. Source: NREL, AWEA and others.

10.3.2 Land Erosion and Subsidence

Land subsidence issues arise when subsurface fluids are removed, resulting in a reduction of fluid pressure on overlying rock (Chorney and Sherwood, 1981). In certain dry steam fields, such as those located in Lardarello, Italy, no land subsidence has occurred (Bowen, 1973). However, in particular regions where water- or steam-dominated fields are present, subsidence issues can be problematic. At the Wairakei plant in New Zealand (the first liquid-dominated field developed), 200 metres of horizontal displacement has been measured over a 10-20 year period (White et al., 2005). The lack of reinjection of waste water in the field over a 50 year period has also resulted in a total pressure decline of 25 bars in the reservoir and over 15 metres of vertical displacement at the center of the subsidence bowl (White et al., 2005; Allis, 2000). Reinjection of waste water is not always practiced, but can help to minimize the potential effects of land subsidence by maintaining the pressure in subsurface environments.

At the Geysers in California, and many other geothermal sites located in humid climates, incompetent rock, clay-rich marine sediments, and high precipitation make an ideal situation for land erosion (Reed and Campbell, 1975). Although natural landslides are known to occur in the region surrounding the Geysers, further aggravation of the land from well drilling and land development has provoked the occurrence of landslides even further. In order to avoid any substantial loss, several wells have been drilled at single sites, and 20% of the surface area above the steam reservoir has been purposely graded to provide level areas for development (Reed and Campbell, 1975). Regulations in site selection and improvements in construction methods have proven to be successful in minimizing any significant and erosion.

10.3.3 Seismicity

Most geothermal resources are found in tectonically active zones where seismicity is already a natural hazard. Human induced seismic activity, however, may also occur as a result of well drilling, hydraulic fracturing, and reinjection of waste water into high pressure systems (Armstead, 1975). Cited by Cameli and Carabelli (1975), one particular experiment performed in Italy over a 40 year period carefully measured the seismic and microseismic activities before and after reinjection. In that particular study, no effects were observed; however, cases of seismicity have been reported at the Geysers geothermal fields and the Rocky Mountain Arsenal in Denver during high pressure reinjection (PIC, 1979; Kagel et al., 2007), and at least 30 other well sites across North America (Nicholson and Wesson, 1992).

When human-induced seismicity is provoked within geothermal fields, it is most often on a microseismic scale (below 2 or 3 on the Richter scale) and too small to be felt by humans (Kagel et al., 2007). With the development of new technologies for extraction of geothermal resources, such as enhanced geothermal systems, the potential for seismic activity has increased. To date, damage to buildings has occurred in Staufen im Breisgau, Germany, due to hydration of anhydrite during drilling (Goldscheider and Bechtel, 2009), and in Basel, Switzerland where a project was suspended after more than 10,000 seismic events measuring up to 3.4 on the Richter Scale occurred over a six day period of water injection (Deichmann et al., 2007). Evaluation of the environmental impacts of hydraulic fracturing and high pressure injection using enhanced geothermal systems is still under review by researchers worldwide (Giardini, 2009; MIT, 2006). These impacts are similar to other activities involving injection of fluids into bedrock, such as waste disposal, CO_2 storage, and enhanced petroleum production (Nicholson and Wesson, 1992), and thus are not unique to geothermal energy. Still, since the outcome and prevalence of seismicity remains somewhat unpredictable, continuous monitoring of the region should be conducted throughout all phases of geothermal development and areas naturally prone to significant seismic activities avoided. A good understanding of the regional stress field is also required (see Chapter 9).

10.3.4 Emissions

Various effluents in the form of incondensable gases and trace elements can be found naturally in subsurface aquifers and geothermal waters. The chemical characteristics and concentrations vary between geothermal fluids and range from potable to highly saline and corrosive (Axtmann, 1975a; Chorney and Sherwood, 1981). For this reason, any emission released from geothermal developments must be both regulated and assessed on a site-by-site basis.

10.3.4a Incondensable Gases

In high temperature geothermal systems, fluids drawn from the deep Earth carry a mixture of gases. A summary of the gas composition found in geothermal fluids along with their typical concentrations can be found in Table 10.1. In the form of geothermal vapours, these gases can be released to the environment from cooling towers, ejector exhausts, silencers, drains and even discharging bores under test and control valves (Chorney and Sherwood, 1981).

Table 10.1 Gas Composition of Geothermal Vapours

Constituent	**Concentration in volume %**	**Remarks**
Ammonia (NH_3)	0 – 5.36	Noxious gas, signifies reducing conditions
Argon (Ar)	0 – 6.3	Minor inert gas
Arsenic (As)	0.002 – 0.05	Health hazard, volatile
Boric Acid (H_3BO_3)	0 – 0.45	Deleterious to plants
Carbon Dioxide (CO_2)	0 – 99	Scale formation
Carbon Monoxide (CO)	0 – 3	Health hazard
Helium (He)	0 – 0.3	Innocuous
Hydrocarbon (C_2 and greater)	0 – 18.3	Potential fuel source, denotes reducing conditions
Hydrogen (H_2)	0 – 39	Provides data on oxidation-reduction environment
Hydrogen Fluoride (HF)	0.00002	Extremely corrosive and reactive
Hydrogen Sulfide (H_2S)	0 – 42	Noxious gas, environmental hazard, corrosion agent
Mercury (Hg)	0.007 – 40.7 (ppb)	Health hazard
Methane (CH_4)	0 – 99.8	Potential fuel source
Nitrogen (N_2)	0 – 97.1	Major inert gas
Oxygen (O_2)	0 – 64	Important for oxidation-reduction reactions, can be corrosive
Sulfide Oxides (SO_2)	0 - 31	Corrosion agent, harmful to environment

Source: Geonomics Inc. (1978, p. 20)

Although concentrations of incondensable gases vary and are dependent upon the geochemistry of the underground reservoir, carbon dioxide (CO_2) is typically the major component of the total gas fraction (average of 78-95%; Axtmann, 1975b). Colourless and odourless, carbon dioxide is a natural component of the air we breathe and may only have a major direct effect on human health at levels above a time-weighted average of 5,000 ppm (CCOHS, 2003). It is, however, the leading contributor of global warming. When released to the environment via waste water, dissolved carbon dioxide may also stimulate growth of many unwanted weeds. In 1968, the accumulated growth of *Largarosiphon major* on intake screens of a dam downstream of the Wairakei plant resulted in a temporary shutdown of its generating station (Chorney and Sherwood, 1981).

The varying concentrations of carbon dioxide emissions from geothermal sources are largely a result of the plant design itself. For each kilowatt-hour of electricity generated at a flash geothermal energy plant, the concentration of carbon dioxide emitted is anywhere from 13 to 380 grams per kilowatt-hour, while a binary geothermal plant will have virtually zero emissions (Table 10.2). In comparison, a geothermal plant using flash technology only emits five percent of the carbon emissions emitted by a coal-fired power plant; the largest contributor of carbon emissions to date (Bloomfield and Moore, 1999).

Table 10.2 Average CO_2 emissions related to electrical generation

	Coal	**Petroleum**	**Natural Gas**	**Geothermal (Flash)**	**Geothermal (Binary)**
g/kWh	1042	906	453	13-380	0

Source: Fridliefsson (2001)

Hydrogen sulphide (H_2S), a colourless gas most notably known for its "rotten egg" smell, can be lethal with short term exposure and concentrations as low as 320 ppm[1] (WHO, 2000). Subtle physiological effects, however, can be detected at much lower concentrations, including eye irritation at 10-15 ppm and loss of olfactory sense at 150-250 ppm (WHO, 2000). When released to the environment via waste water, dissolved hydrogen sulphide may cause unwanted growth of sulphuric bacteria on plankton, limiting the reproduction capacity of fish species (Chorney and Sherwood, 1981; Axtmann, 1975a). When released to the atmosphere, hydrogen sulphide emissions may react with oxygen to produce sulphur dioxide (SO_2). Sulphur dioxide, nitrous oxides, and particulate matter (PM) are identified as 'Criteria Air Contaminants' (CACs) by Environment Canada. Together they form acid rain which can in turn damage crops, interfere with soil decomposition, and disrupt nitrification and nutrient uptake by plants (Armstead, 1978; Chorney and Sherwood, 1981; Hartley, 1978). The combustion of hydrogen sulphide into sulfur oxides is, however, rare in geothermal operations and concentrations of CACs relatively low (Table 10.3). Acid rain however may still be a concern at some distance away from the geothermal facility where other industrial operations may be present (Kagel et al., 2007).

Incidents involving exposure to hydrogen sulphide in geothermal operations are not common, but are still a major concern in geothermal developments due to its severe health implications. While the removal of hydrogen sulphide from geothermal emissions is not always a legal requirement in some countries (WEC, 2007), abatement of hydrogen sulphide has become a routine practice at many geothermal facilities (Kagel et al., 2007). The World Health Organization (2000) also recommends that in

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[1] 1 ppm is equivalent to 1.5 mg/m^3

order to avoid substantial complaints about odour annoyance, hydrogen sulphide concentrations should not exceed 0.005 ppm, with a 30 minute averaging period. Common abatement practices, such as proper ventilation and the use of scrubbers, have already resulted in a significant reduction of hydrogen sulphide emissions at geothermal facilities in the United States despite its significant growth in production capacity (860 kg/hr to 90 kg/hr since 1976; Kagel et al., 2007). The petroleum industry in Canada has a long history of producing H_2S rich natural gas and a strong regulatory environment exists, as well as technical capacity to abate H_2S emissions.

Table 10.3 Summary of air emissions for fossil fuel and geothermal operations (United States)

Average concentrations expressed in g/KWh				
	H_2S	SO_2	NO_x	PM
Coal*	-	4.71	1.95	1.01
Pretroleum*	-	5.44	1.81	-
Natural Gas*	-	0.1	1.34	0.06
Geothermal (Flash)	6.4	0.16	0	0
Geothermal (Binary)	0.03	0	0	0

* H_2S emissions are included in concentrations of SO_2 (result of combustion)
Source: GEA (2007) and IEA (2002)

10.3.4b Trace Elements

In addition to dissolved gases, geothermal fluids may contain trace elements such as mercury, ammonia, hydrogen, nitrogen, methane and radon, as well as minor quantities of volatile species of boron and arsenic (Shibaki and Beck, 2003; Axtmann, 1975a; Chorney and Sherwood, 1981). Although present in relatively low quantities, it is important to understand the potential for trace elements to be a source of air, soil and water pollution (Chorney and Sherwood, 1981). Several cases of chemical contamination have been reported and are of particular interest for their potential to induce harm to the environment and human health.

Mercury, a heavy metal and neurotoxin, has an average concentration of 0-10 ppm in geothermal waters worldwide. It poses greater threat to wildlife and humans when it comes into contact with soil and water, transforming into methyl mercury through biological processes. Methyl mercury, even in very low concentrations can bioaccumulate in the body tissue of animals, moving its way up the food chain as contaminated food sources and drinking water are consumed (Kagel et al., 2007). Boron, also toxic when ingested, has been known to cause marginal and tip dieback in big leaf maple and native oaks of the Geysers region (Chorney and Sherwood, 1981). Arsenic, a known human carcinogen, was found in high concentrations in the Wairakei River; accumulating in a dominant weed species, *L. major* (Chorney and Sherwood, 1981). Health Canada has implemented regulatory guidelines which limit concentrations of boron and arsenic to 5.0 mg/L and 0.010 mg/L respectively (Health Canada, 2006); however, levels of these trace elements in geothermal fluids and steam are typically below these levels (Kagel et al., 2007).

Many of the other trace elements found in geothermal emissions have not been reported to produce any significant amount of harm to the environment or human health, but may be identified as ‘Hazardous Air Pollutants’ and thus are regulated by Environment Canada (e.g. *Clean Air Act* and Guidelines for Canadian Drinking Water Quality). Common practices have also been adopted in geothermal facilities around the world to reduce negative environmental impacts associated with solid waste disposal and the release of chemical effluents. These common practices include the installation of drift eliminators and filters (Kagel et al., 2007), as well as blow-out preventers where drilling into high temperatures or pressures is anticipated (Lunis and Breckenridge, 1991). According to Kagel et al. (2007), noncondensable gases and trace elements typically make up less than 5% of the total steam emitted at geothermal plants in the US. Binary and flash/binary plants have potential for even more significant emissions reductions, emitting zero emissions of incondensable gas and negligible amounts of particulate matter.

10.3.5 Corrosion and Scaling

Silica and sodium are present in some appreciable quantity in nearly all geothermal waters (Rothbaum and Anderton, 1975). Unlike incondensable gases and trace elements however, reinjection methods can not always be used on high-temperature steam/water mixtures prior to treatment where high amounts of dissolved solids are present (Gudmundsson and Bott, 1979). At high temperatures, salinity in combination with hydrogen sulphide, carbon dioxide, or dissolved oxygen (DO) are very corrosive and may negatively impact the operating efficiency of the geothermal plant (Valdez et al., 2009; Koutinas, 1989). Without proper maintenance of the operational equipment, or disposal of waste water, corrosion failures can affect the level of energy production and the well-being of vegetation in the area (Valdez et al., 2009). These effects will be of particular interest in Canada, where average salinity levels can be anywhere from 30 g/L in eastern portions of the Western Canada Sedimentary Basin (WCSB) to 300 g/L in western portions of the WCSB (Fig. 10.1). Several regions of the WCSB also reveal total dissolved solid (TDS) levels as high as 600 g/L; however these anomalies are not believed to be located in regions where geothermal power production is feasible.

In deep hydrothermal waters, silica precipitation occurs as extracted steam cools, giving rise to rapid deposition. The build up of silica deposits will occur in pipes and drain canals, also creating resistance and corrosion problems in the operating equipment of a geothermal plant. Several methods have been used to combat these issues including: 1) allowing supersaturated solutions to polymerize before passing through pipes and equipment; 2) addition of aluminum sulphate or ferric salts; and 3) addition of slaked lime (Thorhallsón et al., 1975; Rothbaum and Anderton, 1975). It has been noted by Rothbaum and Anderton (1975) that formation of colloidal silica in geothermal waters of the Wairakei Plant in New Zealand did cease after one hour of ponding and that discharge of the water could then occur without any problems of silica deposition. At the Hvergerdi plant in Iceland, a 35% dilution of the geothermal fluid with cold water, mixed before flashing at atmospheric pressure, was successfully used to reduce scaling (Thorhallsón et al., 1975). Where fresh water resources may be scarce, preferential treatment of the geothermal fluid with aluminum sulphates, ferric salts or slaked lime may be preferred.

10.3.6 Water Loss

The amount of water loss associated with geothermal developments is largely dependent on the cooling system installed. Water cooling systems in geothermal facilities prevent turbines from overheating and for prolonging facility life but require an average 19 litres of freshwater per MWh (Kagel et al., 2007). This does not include water lost to evaporation in the cooling towers (Kagel et al., 2007; Jennejohn et al., 2009). At the Wairakie plant in New Zealand, a geothermal plant with a 1 to 4 ratio of steam and water, respectively, evaporative water loss occurs at 8×10^5 kg per hour (Axtmann, 1975a). At the Geysers geothermal plant, 75% of the water condensed from geothermal steam in the cooling towers is lost to the atmosphere (Kagel et al., 2007). While having significantly reduced water use requirements, geothermal power facilities using water cooling systems are still dependent on fresh water resources in order to achieve sustainable and continuous base load power.

In arid regions, where water is in short supply, or regions where water resources are in conflict with other industrial processes and developments, air cooling systems may be a better alternative. Air cooling systems generally require more land but do not emit any vapour plumes, resulting in very low emissions and low evaporative water loss. Air cooling systems are typically most efficient in winter months when the contrast of air and water temperatures is greatest, allowing the organic fluid to cool faster (Kagel et al., 2007). Given these characteristics, air cooling systems are not ideal in all climates, but may be considered for use in Canada where winter months sustain relatively cool temperatures.

Water loss in a geothermal power plant is significantly lower than the water loss associated with many other industrial processes. Conventional energy facilities (i.e. natural gas, oil, coal and nuclear) use anywhere from 950 to 2,300 litres of freshwater per MWh (Gipe, 1995; Jennejohn et al., 2009). The adoption of technologies such as hybrid cooling systems and binary, air-cooled geothermal facilities (which use no water for cooling) can further reduce water use requirements and increase plant efficiency. Several geothermal facilities in Hawaii, New Zealand and the Philippines have already achieved 100 % injection on geothermal waters as high as 315 °C, using air cooling towers and a combination of flash and binary technologies (Jennejohn et al., 2009).

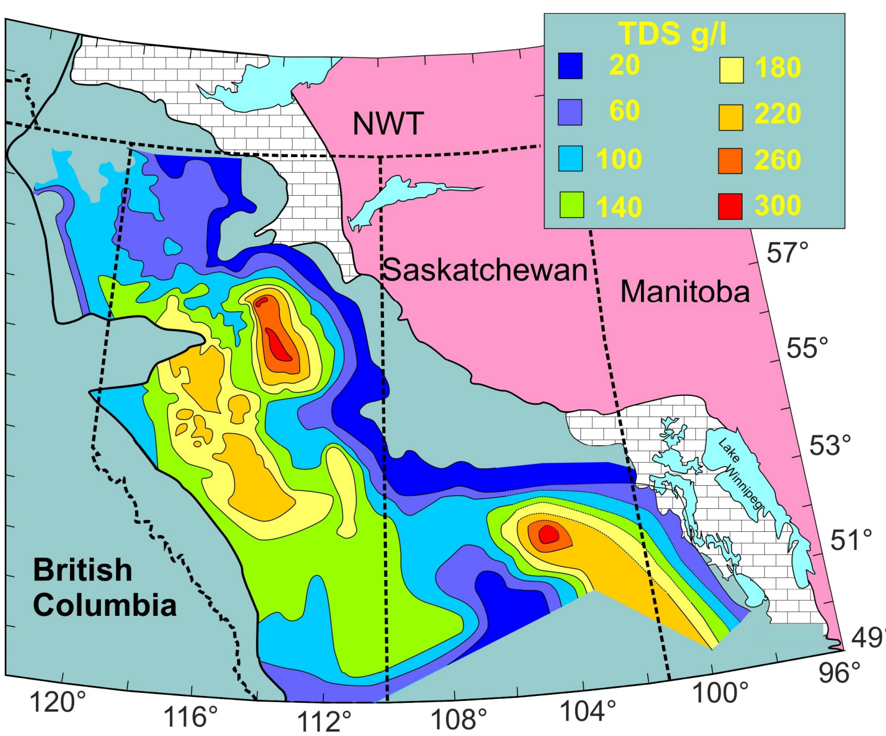

Figure 10.1. Total dissolved solids (TDS) map of the Devonian aquifer system. Source: Grasby and Chen (2005).

10.3.7 Thermal Pollution

As mentioned in Section 10.2, slight changes of temperature in lakes, streams, rivers, and groundwater can affect the spawning activities of fish and the natural refugia of aquatic communities (Hokanson et al., 1973; Marten, 1992: Curry et al., 1995; Acornley, 1999). Reinjection of warm wastewater and production withdrawal can affect the water table and create temperature and pressure gradients in the reservoir, essentially polluting the geothermal system (Barbier, 2002; Kristmannsdóttir and Ármannsson, 2003; Rybach, 2003; Ferguson and Woodbury, 2004; Zhu et al., 2010). Thermal pollution of groundwater can have detrimental impacts on aquatic ecosystems if the polluted groundwater discharges into surface waters. Groundwater discharge into rivers and other surface water systems is often critical to the biotic communities of the area creating important areas of refugia from the heat of the summer and the cold of the winter, particularly for various fish species (Hokanson et al., 1973; Marten, 1992: Curry et al., 1995). Large amounts of heated water can also encourage the growth of unwanted weeds, reducing diversity within ecosystems (Axtmann, 1975a).

Groundwater typically maintains a constant temperature year round; therefore, discharge into surface water bodies buffers seasonal temperature changes (Power et al., 1999) as well as storm flows and seasonal fluvial discharges (Sophocleous, 2002). In summer months, groundwater discharge areas provide river baseflow and are critically important for temperature regulation of organisms as well as the provision of nutrients for increased productivity levels (Power et al., 1999). During the winter season groundwater discharge provides areas of free-flowing water for aquatic species to overwinter, as well as migratory channels between the unfrozen patches (Power et al., 1999). This stabilizing of winter temperatures is also critically important for the survival and development of many fish species' eggs over the winter season (Power et al., 1999).

Many aquatic species have very specific habitat requirements that strongly correlate to groundwater discharge areas, and even small temperature changes can be detrimental to ecosystem health (Table 10.4). A study in Ontario has linked changes in temperatures due to changes in ground surface temperature as a response to aggregate removal (Markle and Schincariol, 2007). Thus, depending on the specifics of groundwater and geothermal developments in an area, along with ecological services of the groundwater, water used for geothermal energy could be viewed either as a resource or a source of thermal pollution (Allen et al., 2003; Ferguson and Woodbury, 2004; Banks, 2009).

Table 10.4 Upper temperature limits for different groups of organisms

Organism	Temperature (°C)
Fish and other aquatic vertebrates	38
Insects	45-50
Protozoa	50
Vascular plants	45
Mosses	50
Eucaryotic algae	56
Fungi	60
Blue-green algae	70-73
Bacteria	>99

Source: Brock (1975)

Such issues of thermal pollution can be largely eliminated by placing well fields at sufficient distances from streams, lakes and wetland, and ensuring, through proper design, that thermally altered groundwater does not travel and discharge into these environments. While there have been some attempts to create guidelines and regulations to address these issues (e.g. Haehnlein et al., 2008), it appears that they need to be evaluated on a site-by-site basis (Ferguson, 2007; Hidalgo et al., 2009).

10.3.8 Noise Pollution

At geothermal power plants, escaping steam at high pressure is very loud and distressing to the ears (Armstead, 1975). During developmental stages, when wells remain open for testing and assessment of production capabilities, noise levels can be as high as 100 dBA in a steam field for several months (Chorney and Sherwood, 1981). Within wilderness areas, where sound levels are typically 20-30 dBA, ecological habitats surrounding the facility may be vacated or mating activities disrupted until habituation to the noise levels occurs (US EPA, 1973; Chorney and Sherwood, 1981).

Noise restrictions can vary by jurisdiction, but according to Occupational Health and Safety Canada (2009), the most common criterion level (Lc)[2] in most Canadian jurisdictions is 90 dBA with a 3 dBA exchange rate[3]. A summary of the typical noise levels for various phases of geothermal development is provided in Table 10.5. In order to reduce the intensity of noise and minimize the impacts of noise pollution, mobile sound attenuation screens and sound mufflers can be installed.

[2] Steady noise level permitted for a full eight-hour work shift.
[3] The amount by which the permitted sound level may increase if the exposure time is halved.

Table 10.5 Geothermal exploration and construction noise levels by operation

Operation	Noise Level (dBa)
Air drilling	85–120
Mud drilling	80
Discharging wells after drilling (to remove drilling debris)	Up to 120
Well testing	70–110
Diesel engines (to operate compressors and provide electricity)	45–55
Heavy machinery (e.g. for earth moving during construction)	Up to 90

Source: International Energy Association (2002)

10.4 ECONOMIC AND SOCIAL IMPACTS

As well as many important environmental effects there will almost always be social and economic issues to consider with geothermal power development. For any development project to initiate and advance it must first undergo an Environmental Impact Assessment and Social Impact Assessment to identify and measure the potential impacts of development. Results from these studies must then be assessed by regulatory agencies and pass intense public scrutiny (Barbier, 2002; Kristmannsdóttir and Ármannsson, 2003). Without a current geothermal power market in Canada, public outreach initiatives may also be necessary to ensure that a common knowledge of geothermal technologies is founded and socially accepted. Regardless of their potential to reduce greenhouse gas emissions, geothermal, like all sustainable energy developments, may compete with other land use developments or reduce the aesthetics of natural landscapes.

Another important constraint on future geothermal power development is that of high initial investments incurred through the exploration, drilling and development of wells and the production field (Pearl, 1976; Barbier, 2002; Elíasson and Björnsson, 2003). Despite low maintenance and operational costs, high initial investments are often a strong deterrent (Barbier, 2002). Such a constraint can be avoided through integrated multiple-use technologies to generate electricity and distribute hot water for direct usage using a cascade approach (Fridleifsson, 2001; Elíasson and Björnsson, 2003; Rybach, 2003). Further implementation of legal and institutional frameworks as well as financial incentive schemes can help promote the use of geothermal energy and development across the globe (Fridleifsson, 2001; Barbier, 2002).

10.5 SUMMARY AND RECOMMENDATIONS

Compared to fossil fuel consumption, geothermal energy production has relatively small greenhouse gas emissions (Barbier, 2002; Rybach, 2002; Elíasson and Björnsson, 2003; Kristmannsdóttir and Ármannsson, 2003; Lund et al., 2004; Kagel et. al, 2007), low environmental impacts and has the potential to provide clean energy at affordable prices, thereby improving the standard of living and socio-economic potential through creation of jobs in many areas (Fridleifsson, 2001; Elíasson and Björnsson, 2003).

In addition to these possible emissions savings by the substitution of geothermal energy for fossil fuels in electricity generation, there exists additional mitigation opportunities through increases in energy efficiency through the use of ground-source and groundwater-source heat pump. Lund et al. (2004) suggests that an immediate reduction in carbon dioxide emissions associated with heating and cooling buildings of 40 to 60% could be realized with the installation of a ground-source heat pump. The same study estimated that the current installed capacity is responsible for a 16 million tonne reduction in annual carbon dioxide emissions. It should be noted that the actual reduction will vary appreciably depending on the source of electricity used to run the pumps and the heat source that the energy is replacing. A study by Blum et al. (2010) supported this idea and estimated that carbon dioxide emissions were reduced anywhere from 15 to 77% depending on the regional energy mix. Additionally, Fridleifsson (2001) indicates that there are substantial air quality benefits to geothermal energy use, suggesting that Reykjavik has some of the best air quality of all the capitals in the world.

The use of geothermal energy in its various forms has substantial potential to contribute to reductions in greenhouse gas emissions, and improvements in air quality and energy security. However, care must be taken to evaluate and monitor the impact of geothermal resource development throughout all phases of development, including continual monitoring after development is completed. In the majority of cases, these issues will be of minor concern, but they should be considered to ensure that they do not become an impediment. Examination of these environmental issues is particularly important at an early stage of development of geothermal resources.

11. GEOTHERMAL COST ESTIMATION AND MARKET RISK

11.1 INTRODUCTION

This chapter examines the costs and cost factors that must be considered in the development of Hydrothermal and Engineered Geothermal Systems (EGS). To the extent that these resources represent an extension of hydrothermal resources in terms of depth, but not performance characteristics[1], the "systems" are functionally the same. The process and degree of difficulty in accessing and developing the system are the basis of the differences in cost.

This chapter summarizes the range of costs and estimated benefits from these geothermal resources using the most recent published data as well as contacts and information from current commercial and research projects. The chapter intends to review the range of costs expected in the development of deep heat resources. It is intended as an overview rather than a definitive study for several key reasons:

- most estimates of drilling and technology costs are proprietary and are typically not released without some protection or aggregation to limit dissemination of the information to competitors;
- the techniques and technologies are evolving rapidly, and figures or estimates may not be strictly current, which can be seen in the range of base year estimates published by the various research and public sources;

[1] Once an EGS system is developed, functionally it is the same system as a more shallow hydrothermal system e.g. a hot circulating fluid is brought to the surface where a conversion technology is utilized to create electric power or steam heat.

- costs vary widely due to factors such as geographic location, geological conditions encountered, drilling success or difficulty and heat characteristics actually accessed.

Data for the conclusions drawn in this chapter are derived from diverse sources including private and public well records, research data from the US National Laboratories, contract research from organizations such as the Geothermal Energy Association and CanGEA and various regional and federal organizations that have commissioned reports or research on costs. Reporting standards differ, and data such as well drilling costs are often proprietary and where used have been aggregated so as to eliminate association with individual projects or investment pro forma.

Wherever possible, data are converted to metric units (metres and °C), but in some instances the references and reporting have been left as they were stated in original research reports in feet and °F. Where costs are reported in Canadian dollars, unless otherwise stated, the base year is shown as 2009.

The following categories are the basis of costs shown.

Near-surface heat exchange or Direct Heat

Geothermal reservoirs of low to moderate temperature 20 to 150 °C, used for heating homes, offices, and greenhouses; in aquaculture and food-processing plants; and a variety of other applications. System life is estimated at 25 years for inside components and 50+ years for the ground loop and wells where applicable.

Hydrothermal systems

Well and surface conversion technology that has been focused to date on natural geothermal reservoirs with both high porosity and high permeability. These systems are limited geographically and are not typically located near load, necessitating high voltage transmission access. The electricity generated is particularly well suited to baseload grid operations where it competes favorably with coal or nuclear generated power. The lifespan of the installed well systems is assumed to be in the 25 to 30 year range before re-stimulation is needed. Water recharge may be necessary with these systems, typically provided by injection of surface water from reservoirs or municipal waste treatment.

Engineered Geothermal Systems (EGS)

EGS systems are associated with high temperature, low permeability rocks that are engineered into technically and commercially exploitable reservoirs by fracturing existing and/or creating new heat exchange surfaces of the rock matrix and then establishing fluid flow systems for the purpose of generating electricity in surface conversion facilities. For purposes of this section, this resource is deemed to become available at temperatures above 180 ^{o}C although an accepted industry standard usually references >250 °C with an effective limit of approximately 300 °C[2]. The lifespan of subsurface improvements is assumed to be less than hydrothermal facilities, with re-stimulation necessary at intervals of from 6 to 10 years in each well bore, and well lifetimes before resting at < 25 years.

11.2 USE AND LIMITATIONS

This section is not intended to be definitive in the sense that every well site, even areas between sites, will be unique in their geological and stratigraphic relationships, as well as their access or proximity to transmission systems. Each power system in turn will have unique pricing, uplift and transmission charges, and each electricity dispatch area will make different demands on, and payments to, baseload energy providers. Finally, arrangements with financing agencies will necessarily reflect the competitive cost of capital in the marketplace at the time a project is proposed and will reflect the history of operations of the customer, the expected risk profile of the project, and the presence or absence of arrangements such as power purchase agreements to govern payments.

Earth energy and geothermal systems generally represent a continuum of depth and heat conversion from ground source heat pumps, through hydrothermal resources and into the zone of hot-dry-rock referred to in this chapter as EGS. In each case, drilling and heat recovery are the core concepts at work, reflecting the emphasis put on well drilling expertise as well as the nearly linear relationship of costs to depth of wells drilled in all applications.

[2] The limits are practical in nature at this point, as opposed to theoretical. Although there are power conversion technologies available for generation at temperatures <180° they are unproven in grid operations to date and at temperatures approaching 350 °C, the telemetry and drilling operations become unstable.

Most of the cost estimates for existing and developing projects reflect the experience and knowledge based in hydrothermal systems, with extrapolation to the deeper zones where fracturing and stimulation are being attempted to gain access to hot, circulating fluids. In this context, EGS should be seen as a continuation of hydrothermal systems that may be limited due to naturally fractured and flooded substrata in limited geographic distribution.

Hydrothermal systems are extremely cost effective elements of electric baseload power systems where they can be located near relatively shallow thermal vents or hot hydrologic systems for instance at the Geysers in California. When comparing costs, however, since EGS systems are not commercially viable at this time, the numbers shown in this chapter must also be seen as guidelines that represent the engineering practices known currently, which are then subject to qualifications and estimates made in the context of current knowledge and technology.

11.3 GEOTHERMAL RENEWABLE ENERGY OVERVIEW

Both hydrothermal and engineered geothermal systems are, by definition, dependent on heat in order to deliver benefits in the form of delivered heat or steam, or electricity generation. Since they both depend on accessing heat at depth, the critical element of their operation(s) is the nature of the wells that provide that access. Ultimately, power conversion systems provide the end use energy in a variety of forms and they in turn are dependent on access to energy transmission systems, whether through insulated pipes or high voltage transmission systems.

With this short introduction in mind, it is convenient and useful to divide the issues of economics, costs, benefits and financing into 6 categories. These include:

a. Exploration, confirmation and resource evaluation
b. Drilling operations and well development
c. Power system development
d. Market operations and financial risk
e. Control of externalities and remediation

Each of these categories implies a certain knowledge level (or gap) and implicit risk either in engineering, operations or unforeseen impacts. This leads to a need to express the costs as well as benefits in terms of ranges and probabilistic outcomes. The geothermal field is not a mature industry in the sense we treat manufacturing or service companies; much of the knowledge of subsurface structure and characteristics including heat gradients and reservoirs is inferred, often at inconsistent intervals or from associated wells completed for oil and gas observations.

Within each of these categories, there are no industry standards, only an appreciation that development will be governed by subsurface characteristics on a field-by-field or regional basis. The industry expects a learning curve within each individual field or zone (MIT, 2005), but not necessarily a matching curve between regions or at increasing depth. In addition, cost estimates for power conversion technologies are changing rapidly as technology efficiency increases and the prices paid for delivered base load energy change.

Geothermal power is produced at steady and predictable rates. As such, it typically forms a portion of the baseload power contribution for electricity generation systems. A moderate heat source plant with a binary conversion power facility can expect installed costs in the range of $1,500[3] kW at 200 °C which is competitive with the most efficient alternatives as shown in Figure 11.1. Differences in merchant, investor-owned and publicly-owned facilities reflect the competitive cost of capital, long term contracts and pre-existing power purchase agreements.

The products commercially available from geothermal operations include electricity, direct heat, steam heat, minerals from brine solutions (such as lead, zinc and other dissolved heavy metals) and the potential for storage in retired well fields at some point in the future.

Geothermal energy exists and provides rewards to investment solely on the basis of sales to power and energy markets. Table 11.1 below highlights the broad roles and competitive opportunities for renewable energy in the current electricity markets.

[3] National Renewable Energy Laboratory, NREL,2010,http://www.nrel.gov/analysis/tech_cost_oandm.html

Table 11.1. Typical market drivers for renewable energy

Driver	Developed Markets	Emerging or not-mature Markets
Power prices	✓	✓✓
Demand Growth	✓✓	✓✓✓
Reliance on Energy Imports	✓✓✓	✓✓✓✓
Environment	✓✓✓✓	✓

Source: Ormat Technologies, Inc., presentation by Rahm Orenstein at Greenpower Conferences March 2009 Geothermal Innovation and Investment Conference

In terms of capacity factors relative to other existing and emerging technologies, geothermal energy has a great advantage, especially in terms of dispatchable baseload power supplies. Figures 11.1 and 11.2 illustrate this characteristic in two areas, namely overnight capital costs and operating costs by technology. The comparison with other baseload energy sources such as coal, nuclear fission and hydroelectric systems illuminates the higher certainty of geothermal capital costs relative to other technologies but a wider range of expected operating costs by comparison with nuclear power systems.

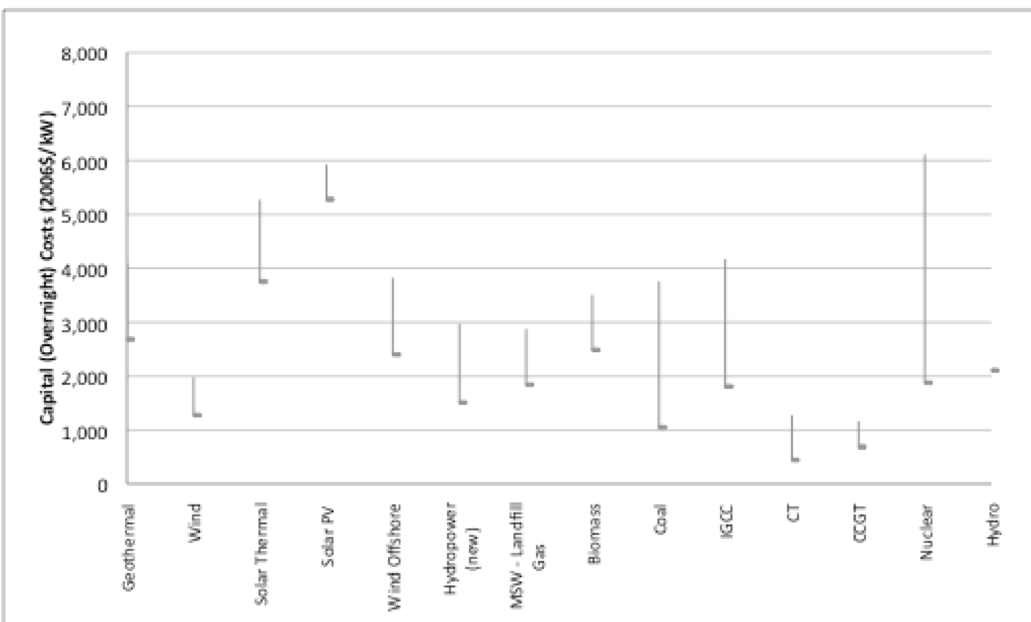

Figure 11.1. Overnight capital costs of comparable renewable technologies. Source: NREL (2010).

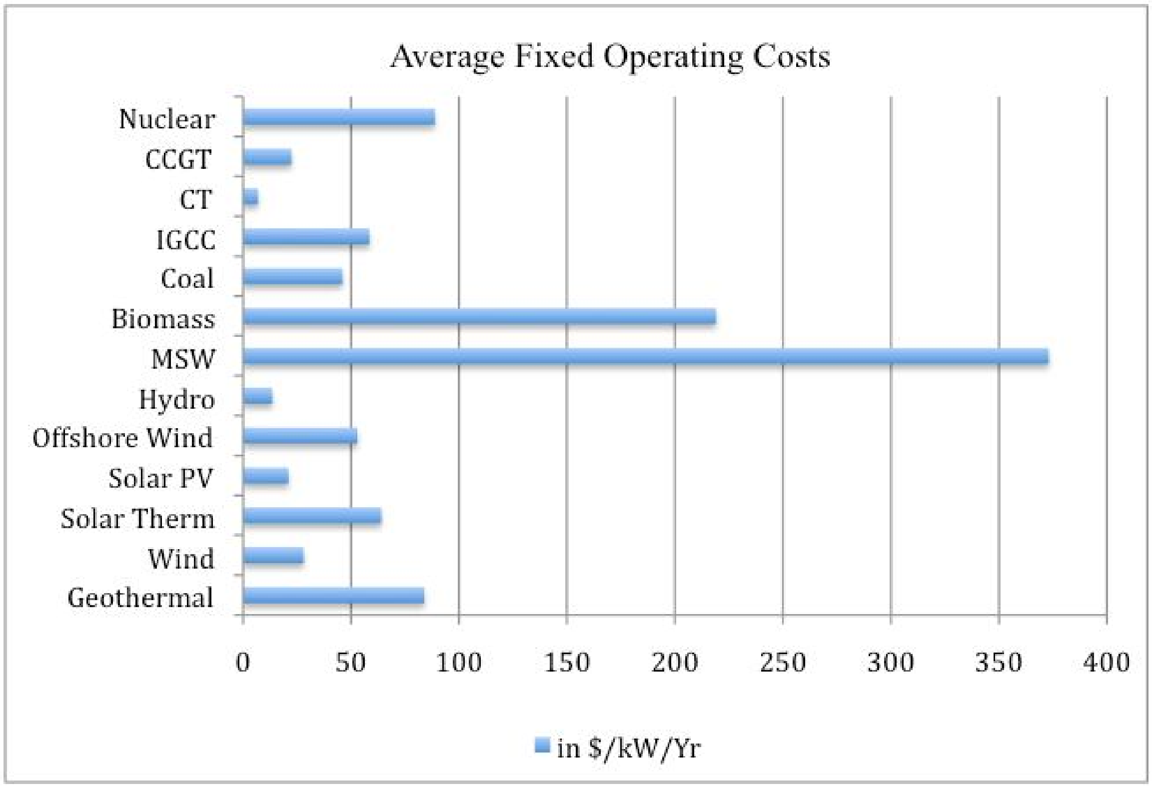

Figure 11.2. Fixed operating and maintenance cost for energy technologies in 2006 $/kW yr. Source: NREL (2010).

Power costs[4] for most technologies are estimates, depending on operational conditions, age, and fuel costs. As well, many capital costs such as geothermal surface power conversion facilities are not commonly published and reflect very location-specific bids and construction costs. The consequence is that estimates made of costs are typically expressed as ranges with production costs expressed as levelized cost(s) of energy (LCOE) which include capital and operating costs over the expected life of the project. This is usually correlated with the financing life for the project, typically about 30-35 years. Most projects will exceed this lifespan but only after re-stimulation and perhaps periodic rest periods to allow reservoirs recover.

For instance, Geothermix has determined that in terms of costs, the "minimum achievable power cost is insensitive to plant capacity" is on the order of 3.5¢ / kWh, a figure they cite as being "relatively insensitive to well productivity, drilling cost per well or well productivity decline

[4] Most of the technologies included in Figure 11.2 generally utilized in grid operations are compared in terms of operating costs on a dollars per kW per year basis, and include thermal generation from fissionable nuclear facilities, pulverized coal, and gas turbines both simple and combined cycle, to renewable generation technologies from wind both onshore and offshore, solar thermal and photovoltaic to methane gas generation from municipal solid waste facilities, as well as geothermal baseload generation capacity.

rate" (Sanyal, 2004). Energy cost surveys for estimating capital and Operation and Maintenance (O&M) are not consistently updated, especially for renewable generation sources and, consequently, are reported in the most recent year available.

Grid operations and dispatch, as well as competitive bidding for generation are critically dependent on the capacity factor of the available technologies. They not only provide a metric of potential performance, but when combined with availability (hours available minus maintenance and unexpected outages) demonstrate a high measure of reliability in terms of system operation. These are shown comparatively in Figure 11.3.

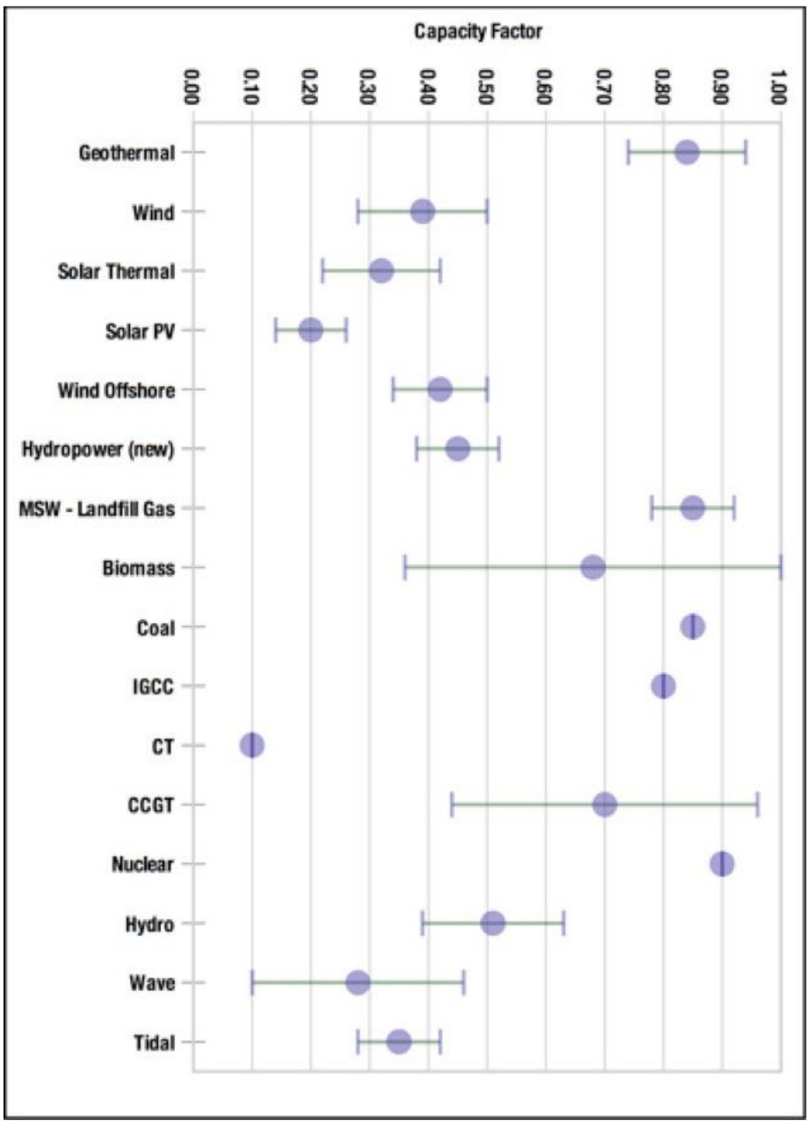

Figure 11.3 Comparison of energy technology factors. Source: NREL (2010).

It is worth noting that the capacity factor of geothermal energy is higher than most competitive technologies and on a par with nuclear baseload. The availability (typically >97 %) is higher than competitive thermal technologies as well.

The combination of overnight capital costs, fixed and variable operations and maintenance costs and the capacity/availability combine to give us an expected average cost of delivering energy commonly measured as levelized annual cost of energy or LCOE. These are shown for a wide array of technologies in Table 11.2 where they are differentiated by merchant, investor and privately-owned utility.

11.4 COST CATEGORIES FOR GEOTHERMAL ENERGY

Power generation, even in a fully regulated environment, is an exercise in cost control, efficiency and the use of best available technologies. In each phase of power development and distribution, there are corresponding risks that can be expressed as a function of the probability of occurrence and the loss or cost of that occurrence, as well as frequency and/or duration of the event.

Since the costs are effectively estimates and will vary by operator as well as area, they are expressed as a range in addition to the probability of occurrence. All costs are expressed in terms of US dollars base year 2009.

Table 11.2 Average levelized costs of generation by technology

Summary of Average Levelized Costs - In-Service in 2018

In-Service Year = 2018 (Nominal 2018 $)	Size	Merchant			IOU			POU		
	MW	$/kW-Yr	$/MWh	¢/kWh	$/kW-Yr	$/MWh	¢/kWh	$/kW-Yr	$/MWh	¢/kWh
Small Simple Cycle	49.9	422.48	1028.23	102.82	330.89	805.60	80.56	323.59	394.09	39.41
Conventional Simple Cycle	100	398.71	970.39	97.04	311.27	757.86	75.79	307.31	374.26	37.43
Advanced Simple Cycle	200	354.72	431.66	43.17	294.42	358.41	35.84	308.73	250.66	25.07
Conventional Combined Cycle (CC)	500	1052.85	171.58	17.16	980.42	160.01	16.00	920.06	150.42	15.04
Conventional CC - Duct Fired	550	1009.36	176.24	17.62	937.12	163.87	16.39	876.57	153.55	15.35
Advanced Combined Cycle	800	975.62	158.99	15.90	910.16	148.54	14.85	855.45	139.86	13.99
Coal - IGCC	300	2422.09	178.14	17.81	911.10	142.48	14.25	723.39	113.17	11.32
Nuclear Westinghouse AP1000 (2018)	960	1139.56	342.41	34.24	1929.55	273.07	27.31	1171.66	166.85	16.68
Biomass IGCC	30	1006.20	168.48	16.85	966.60	161.86	16.19	841.43	140.97	14.10
Biomass Combustion - Fluidized Bed Boiler	28	1054.11	160.43	16.04	974.35	148.32	14.83	837.48	127.60	12.76
Biomass Combustion - Stoker Boiler	38	1061.71	158.22	15.82	998.40	148.82	14.88	890.68	132.88	13.29
Geothermal - Binary	15	666.46	129.42	12.94	695.05	136.73	13.67	591.29	124.98	12.50
Geothermal - Flash	30	646.49	120.72	12.07	674.90	127.66	12.77	580.53	117.99	11.80
Hydro - Small Scale & Developed Sites	15	315.28	164.59	16.46	304.10	159.84	15.98	220.33	120.27	12.03
Hydro - Capacity Upgrade of Existing Site	80	157.31	77.80	7.78	152.81	76.09	7.61	115.80	59.88	5.99
Ocean Wave (2018)	40	511.74	261.71	26.17	485.22	249.02	24.90	361.85	189.33	18.93
Solar - Parabolic Trough	250	500.65	298.64	29.86	483.85	288.92	28.89	427.05	256.13	25.61
Solar - Photovoltaic (Single Axis)	25	512.14	305.50	30.55	494.76	295.43	29.54	436.12	261.57	26.16
Onshore Wind - Class 3/4	50	357.14	127.19	12.72	337.44	120.59	12.06	248.91	90.69	9.07
Onshore Wind - Class 5	100	363.57	114.06	11.41	343.90	108.27	10.83	255.53	82.02	8.20
Onshore Wind - Class 5 (2018)	350	731.39	214.16	21.42	690.08	202.78	20.28	504.75	151.21	15.12

Source: Energy Commission

11.4.1 Exploration, Confirmation and Resource Evaluation

Every project, whether an extension of existing operations, commissioned, or undertaken on a "spec" basis, must evaluate alternative sites or fields for potential development. In the case of traditional hydrothermal resources, these are likely to be found in previously mapped or known areas, typically in the proximity of faults or areas of intrusive volcanic activity. In the case of EGS projects, theoretical work suggests that there is a wide distribution of the resource accessible at varying depths to appropriate heat levels virtually anywhere in the world. The limit, of course, is in the concept of available heat, which although ubiquitous generally, may be available at prohibitive cost levels. In most cases, current non-commercial exploration of EGS facilities will be coincident with existing or shut-in oil and gas operations where subsurface data are available on temperature, geological formations and the presence or absence of water.

In terms of cost control, the site selection and evaluation is critical, not only to the investment potential of the project but to the power generation potential that it represents. The objective ultimately is to access resources with high heat potential and low gradients that can be developed at the least drilled depth. In other words, for EGS facilities, they effectively become extensions of hydrothermal zone projects[5] with the addition of the need for fracturing and stimulation with hydraulic fluids in order to create a heat reservoir with circulation.

Exploratory wells drilled during this phase are effectively "wildcat" and may have success rates of 25 %, on average. Improving this success rate is likely in test wells within a region or related geographic zone, but can fall off with distance. The success rate is increased with proximity to, or re-drilling of, oil and gas wells (Blackwell and Richard, 2009). Following discovery of a promising formation, developers will sequentially test fracturing success, flow rates, temperature, water table drawdown and thermal conductivity, estimating potential production capacity. Expected costs during this phase may range from ~$100 to $150 US per kW for a

[5] This "zone" is meant to represent those project depths generally less than 3km in depth, but not necessarily also near hot hydrologic formations.

developed production quartet[6]. The figure is variable depending on the number of unproductive wells, fracturing, and flowing success and stability of the stimulated reservoir[7].

Table 3 presents a summary of typical costs associated with the exploration phase of a project, where the geologic characteristics are mapped generally at the surface or inferred from work such as oil and gas or water production wells, but not characterized for geothermal development (Sanyal 2004).

Table 11.3 Summary of exploration costs in 2009 dollars

Method	**Unit**	**Cost per Unit**
Administration	project	10 % of total exploration cost
Drilling slim hole well	foot	166
Drilling slimhole temp log	well	59,401
Drilling TG hole(s)	foot	18
Geochem survey	project	35,640
Geology field mapping	project	23,760
Geophysics ground magnetics	project	14,850
Geophysics gravity	project	29,700
Geophysical study resistivity	project	23,760
other contingencies	project	11,880
Reporting forms	project	10 % of total exploration cost
Well test 3-10 days	well	47,520

Source: California Energy Commission, GeothermEx (2004).

11.4.2 Sensitivity

Geothermal power systems demonstrate a wide range of performance, dependent on many variables including the number of wells and temperature, as well as the efficiency of surface conversion technology. Individual well performance depends simultaneously on successful stimulation and flow rates in zones of useful heat production. One way to imagine the outcome in terms of delivered cost(s) of power is to portray the operations in terms of a range of potential cost reductions (i.e. increased flow rates at useful temperatures will result in

[6] US DOE, MIT – These costs can range up to $200 US per MW depending on drilling depth, access and lithological conditions. personal communication, J. Weisgall, MidAmerica Energy Group (2010)

[7] As a rule of thumb, most "projects" are assumed to develop field production targets of 50–60 MW, using triplets or quartets of 3 or 4 injection to 1 production well.

corresponding lower costs of operation). Table 11.4 illustrates the combination of depth and heat variations on flow rates and output costs with corresponding characteristics of overall project or plant size.

11.4.3 Heat Gradient and Planning Drilling Depth

The geothermal gradient is the rate of increase in temperature per unit depth in the Earth. It varies with location (as illustrated in Chapter 5) and is typically measured by determining the bottom open-hole temperature after borehole drilling. In stable tectonic areas a temperature-depth plot ultimately will converge to the annual average surface temperature.

Heat flow[8] is determined by multiplying the borehole temperature gradient times the thermal conductivity. This can be useful in plotting isothermal contour lines to show minimum drilling depths to constant temperature zones (for instance a zone of acceptable temperature for power conversion that we might establish as 150 °C. In this context the words geothermal and heat flow become synonymous.

For reference, the deepest hole measured in the US is approximately 9,100 metres, although most wells are less than 3,100 m. To determine the Earth's internal temperature at any depth below the capabilities of normal well drilling, multiple data sets typically are synthesized. The data used include thermal conductivity, thickness of sedimentary rock, geothermal gradient, heat flow and surface temperature. When sedimentary rocks are less than 4 km deep, a constant basement thermal conductivity of 3.0 W/m K is assumed. The range of regional temperatures at 4 km thus ranges from less than 70 to over 150 °C[9].

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[8] Fourier's law of heat flow applied to the Earth gives. $Q = K\ \delta T/\delta z$ where Q is the heat flow at a point on the Earth's surface, K the thermal conductivity of the rocks there, and $\delta T/\delta z$ the measured geothermal gradient. A representative value for the thermal conductivity of granitic rocks is K = 3.0 W/m K. Hence, using the global average geothermal conducting gradient of 0.01 K/m Q = 0.03 W/m². This estimate, corroborated by thousands of observations of heat flow in boreholes all over the world, gives a global average of 87×10^{-2} W/m².

[9] SMU Geothermal Project, http://smu.edu/geothermal/heatflow/heatflow.htm

Table 11.4 Sensitivity of plant cost to flow rate and temperature

Case Characteristics	Higher Flow Rate / Well	Reduced Rate Thermal Decline	Decreases in Production Well Costs	Decreased injection Well Costs	Increased Power Plant Efficiency	Increased Project Size
3.75 km @ 275°C	-45%	-7%	-8%	-1%	-14%	-16%
3.5 km @ 250°C	-47%	-7%	-9%	-2%	-18%	-14%
3.5 km @ 180°C	-64%	-36%	-13%	-5%	-20%	-16%
4.5 km @ 200°C	-56%	-21%	-24%	-17%	-30%	-9%
6.6 km @ 200°C	-60%	-12%	-17%	-8%	-22%	7%

Source: for Tables 11.4 AltaRock (2010) and MCM (2010)

11.4.4 Drilling

The most significant cost factor in all geothermal operations is associated with drilling and well completion. In this area the cost is directly correlated with drilling depth with an estimated coefficient of "determination" of $R^2 = 0.558$ which effectively explains 56% of the cost variability of wells (including the variation of rock formation, trouble and the range of wellbore and casing strings). There is a not-surprising correlation between wells drilled in relatively shallow sedimentary basins or completing existing oil and gas wells and "lower" costs compared to deeper wells that may encounter corrosive brines, higher wall temperature and high pressures.

For hydrothermal resources, the rock permeability, resident temperatures and pressure, and the field size are the key indicators of the productive capacity of the well system. Ultimately they will determine productivity, capacity and, by inference, the number of wells needed to economically develop the site while maintaining a useful residual heat balance. Useful temperature ranges will vary from 150 °C to 250 °C. Well productivity will depend principally on useful temperatures and rates of flow of the water or brine solution. According to GeothermEx, there is a roughly linear correlation between well productivity and temperature:

Well Productivity (MW) = resource temp (°F)/50-3.5

Over time, well productivity will decline due to temperature loss. This loss in productivity which can be dealt with in several ways, including rest for the producing well, drilling additional producing wells beyond the estimate of production needs and active reservoir management.

Well costs are not a linear function of depth, but additionally reflect, temperature, extent of casing employed, difficulty in drilling, and lithologic characteristics (Augustine et al., 2006). Table 11.5 below illustrates the expected costs for wells alone under average conditions.

Table 11.5 Average drilling costs

Drilling Interval (ft)	Ave Depth Meters	Ave Depth Ft	Costs 2009 $
1250-2499	557	1826	0.253
2500-3749	964	3162	0.298
3750-4999	1329	4359	0.335
5000-7499	1912	6272	0.606
7500-9999	2613	8572	1.128
10000-12499	3380	11087	2.270
12500-14999	4092	13424	3.293
15000-17499	4868	15969	5.771
17500-19999	5648	18526	12.480

Source: Adapted from Augustine et al. (2006).

As a general rule, we would expect *improvement costs* to be arrayed roughly in the following groups:

Fixed Costs, including location, site preparation and roads	8 - 12 %
Fixed Costs, including equipment, casing, cement, coring etc.	23 - 27 %
Well Completion, including perforation, site remediation	4 - 6 %

11.4.5 Stimulation and Flow

In the case of EGS facilities, fracturing, stimulation and flow control will be critical for overall well and system performance. This field is in development and can be considered experimental, although there are completed systems that can be used to illustrate the potential range of costs and the expected cost outcomes when in operation.

Recent work in diverters and flow control will ultimately reduce risk and uncertainty, both in the investment community as well as for utilities anticipating the use of geothermal as replacement or for marginal expansion of baseload capacity. These costs are not known but are anticipated to be in the range of stimulation costs shown in Table 11.7, where they will increase the effect and efficiency of stimulation attempts in new fields.

Recent field evidence suggests there is a clear effect of stimulation in strategic zones for deep EGS wells. Stimulation cost ranges from $200,000 to $450,000 per zone. The cost per kW of improvement experienced is approximately $750, with each stimulation zone generating a range of 1-3 MW. Expected well performance can be improved as well using a combination of chemical diverters (where appropriate given the lithology) and stimulation. As shown in Table 11.6, recent evidence from various existing locations, where multiple wells and surface generation allow comparison, shows the benefits of combining diverter loss control and maximizing the fracture zones for circulation.

Table 11.6 Cost comparison - diverter/multiple fracture stimulation on the cost of power

	Project	Current Technology	3 Stimulations	Current Technology	3 Stimulations
		Binary		Flash	
Soultz	$/kW	$16,230	$5,524	$12,644	$4,869
	¢/kWh	37.15	10.1	25.1	9.79
Cooper Basin, AU	$/kW	$15,251	$7,036	$12,945	$4,793
	¢/kWh	31.73	13.21	25.12	9.42
Newberry, Or	$/kW			$6,431	$2,776
	¢/kWh			13.1	5.61
Mt St Helens, Wa	$/kW	$16,690	$5,690	$14,627	$4,804
	¢/kWh	35.79	10.35	28.57	9.56
Ithaca, NY	$/kW	$29,665	$8,574		
	¢/kWh	68.3	15.65		

Source: S.Petty, D.Wyborn, R.Baria personal communication

11.4.6 Cooling Rates and Reservoir Design

The heat reservoir literally contains the lifeblood of the system whether hydrothermal or EGS. In addition, the lifespan of the reservoir as well as thermal retention become critical elements of the EGS operation. Forecasting this relationship is critical to estimating the potential financial returns from field development and can be portrayed graphically as shown in Figures 11.5 and 11.6. Thus, the economic relationship of the entire system will be tied to reservoir replenishment, if necessary, which in turn will be based on a continuing understanding of reservoir performance. This relationship is directly tied to power delivery and cost. The cost of maintaining the reservoir is difficult to forecast, since it will depend on the cost of makeup water (if available and usable within the operations permit) and actual volumes needed to maintain reservoir stability.

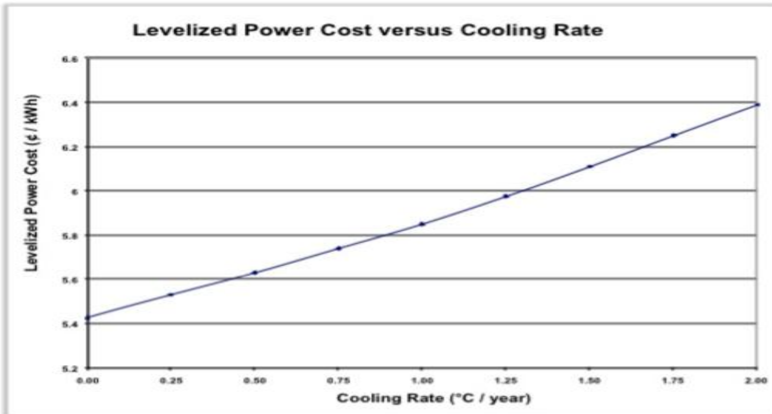

Figure 11.4 Levelized power cost versus cooling rate. Source: AltaRock (2010) and DOE (2009)

The reservoir must be managed consistently in order to maintain reservoir integrity and longevity. Management includes tracking the cooling rate of the reservoir as well as rate of pumping from the well system. The result is a site development system that optimizes generation in terms of well depth, stimulation and flow rates and expected (managed) temperature levels, all in the context of current and forecast power prices.

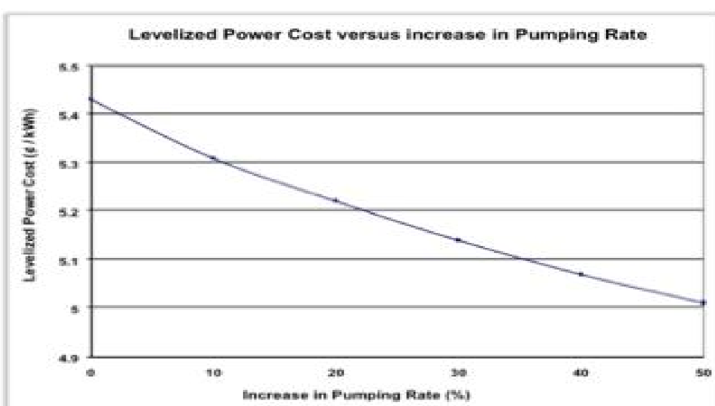

Figure 11.5 Levelized power cost versus increase in pumping rate. Source: AltaRock (2010) and DOE (2009)

This management plan should include an estimate, when planning the reservoir and system design, of expected reservoir temperature and the corresponding heat flow over the forecast lifespan of the resource field as shown in Figure 11.6.

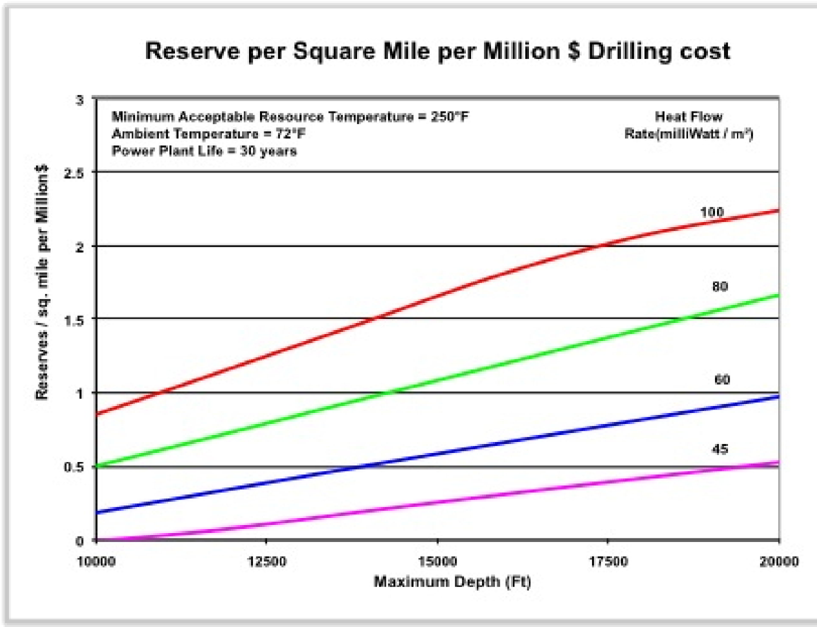

Figure 11.6 Reserve per square mile per million $ drilling cost.

11.4.7 Improvement Costs

Wells, power conversion and operation are capital and cash intensive activities. Published values for drilled and producing hydrothermal wells have a range of cost from $3,500 to $5,000 (in 2009 $) per installed kW[10]. These wells are typically drilled in relatively high permeability formations that minimize the cost of the well field, which is likely to represent from 25-50 % of total field costs for the operation. EGS will add to this cost structure significantly in terms of the core element, namely well costs that are by definition deeper and require an extra step of stimulation of the surrounding rock mass in order to obtain circulation paths for heat conducting fluids. As a consequence, the well costs will begin at approximately $5,000 per installed kW and may exceed $9,000 for deep wells that do not reach high temperatures. This increase in local costs may drive well field costs to represent 60-80% of total project costs for EGS.

[10] Geothermal Strategic Value Analysis, California Energy Commission, 2005, CEC-500-2005-105-SD

11.5 MARKET OPERATIONS AND FINANCIAL RISK

Investment in geothermal developments is not undertaken lightly. These projects represent risks ranging from efficient access to resources, timely and cost effective drilling and construction and the penetration of markets where power purchase contracts as well as access to transmission facilities must be gained. This implies long time periods before a break-even point is reached and the projects begin to generate net profits.

Commercial bank loans to finance activities are expensive and reflect the competition for energy development capital, and the premium put on technologies that are perceived to be out of the mainstream (for instance wind energy is a preferred public policy option but still commands high risk premium rates). The upshot of this is that many development projects must use their own capital or find investors willing to share risk and ownership (equity) in return for very long period returns. Here, high risk translates to required high rates of return.

11.5.1 Cost of Power and Risk

Geothermal power is typically supplied to the grid as baseload energy, a category that demands (and rewards) consistent low cost electricity. Estimating the cost of delivered power is uncertain given the number of facilities currently operating, but is projected to decline at a rate which will be competitive within the next 15 years to coal fired production given current levels of technology[11].

Using the current costs of hydrothermal power, we can forecast the likelihood or probability (P) of generating average prices, based on deeper depth and higher temperature ranges such as those which might be encountered in EGS operations. These are shown in Table 11.7 and illustrate the correlation of, and the advantage conferred by, deeper wells and higher temperatures.

[11] This cost was estimated in the MIT report to approach 5 cents / kWh for EGS in 15 years, roughly the same as coal when escalated by inflation and assuming no extraordinary environmental control costs.

Table 11.7 Estimates of power cost at depth and temperature with average well cost

	¢/kW with 90% Prob.	¢/kW with 50% Prob.	¢/kW with 10% Prob.
3.75 km @ 275°C	24	15	10
3.5 km @ 250°C	27	17	12
3.5 km @ 180°C	38	21	13
4.5 km @ 200°C	39	24	16
6.6 km @ 200°C	156	81	46

Source: MCM (2010)

The primary project risk characteristic for geothermal energy lies in the identification, assessment and development of the resource itself. Drilling difficulties and risk of overrun or failure to develop adequate heat reserves will all contribute to higher cost and consequent diminished returns, investor losses, or failure to meet contract specifications such as those determined in Renewable Portfolio Standard programs. There is also a category of market risk to be considered, since baseload generators typically are price takers where the marginal price is set by grid operators and contracts are entered for long periods of time. Finally, there is the risk of field performance declining due to changes in geological conditions, or excessive demands being made on a given reservoir. All of these categories of risk will be taken into account by investors, whether private or public, as the phases of the project are initiated and completed and electricity generation begins. Market risk can be offset by the presence or absence of subsidies.

However, since wells and drilling costs represent such a high fraction of total geothermal system costs, the probability of achieving production goals will be a function of the amount of drilling undertaken, the temperature finally penetrated and the value when sold in the market. This is illustrated in Table 11.8, which provides an illustrative sample of full system development and *expected returns* in a greenfield operating site (not including exploration costs).

Table 11.8 Illustrative potential returns in kW from typical geothermal wells to 3 km

	Project Cost	Low Ret kW	Target kW	High kW	Cost $/kW	Expected Gross	Expected Net
First 6 months							
Well Drilling & Optimization	4125000	<0	1240	2229	3,327	675,000	na
Expected kWg		10500	10500	10500			
Real or Actual		9040	11700	12700			
Optimized Parasitic Load in kW		1800	1500	1250			
Plant Output Mwe (annual)		7.2	10.2	11.5		5,750,000	4,700,000
2nd 6 months							
Optimized improvements well, water etc.	5,000,000	2,200	3,100	4,300	$1,608		
Plant Output in kWg		11,250	14,900	17,000			
optimized parasitic load in kW		1900	1750	1650			
Plant Output Mwe (annual)		9.4	13.1	15.4		7,380,000	6,000,000
Long Term (>12 mo)							
Acquire Water supply and wells	31,000,000	3,400	5,900	7,600	5,200	4,760,000	na
Build Wellfield Control	2,400,000	3,400	5,900	7,600	5,200		
Total Improvements	33,400,000	3,400	5,900	7,600	5,800		
Plant Output in kWg		14,700	21,000	25,000			
Optimized parasitic load in kW		2,000	2,000	2,000			
Plant Output Mwe (annual)		13	19	23		11,500,000	9,540,000
Totals	42,525,000					24,630,000	20,240,000

Source: MCM (2010), derived from Geothermix and AltaRock estimates (2009).

Private equity invested in overall geothermal projects can be expected to yield an average annual rate of return of over 15 %[12]. When the project is broken down into discrete elements such as exploration and initial drilling, higher risk premiums are likely to be demanded in the marketplace. Time from start to production must also be taken into account. Projects should expect a range of 3 to 5 years for projects that are developed in identified zones of good resources and where drilling depths are not extreme (i.e. < 5 km).

The initial phases of development[13] including drilling and fracturing may proportionately represent a higher fraction of the total investment cost and ultimately demand a higher fraction of the return in order to amortize the debt. For instance, GeothermEx points out that "$150,000 borrowed over 4 years at 17 % corresponds to an actual cost of 150*(1.17)4 = $281/kW when the power plant is finally on line and begins to pay back".

Further, permitting and sighting control can represent additional time and uncertainty as the power plant and interconnection protocols are developed. These delay costs can represent a significant portion of borrowing costs.

In the GeothermEx report, they developed a generic table showing the impact of delays on exploration costs (Fig. 11.7), which serves as a representative comment on the magnitude and impact of these costs (these are shown in 2005 costs and are not updated in the example). The table and chart show the change in expected value of $100 and $150 capital investment when a 17 % rate of return is calculated and the effect on project viability.

The range of sensitivity in terms of delivered power cost reveals the critical role of the variables discussed above in terms of long term levelized costs for new geothermal developments[14]. The value of additional stimulation and overall returns as a function of costs of operations is clear in Figure 11.8 below as well as the critical role played in terms of managing overall Operations and Maintenance costs.

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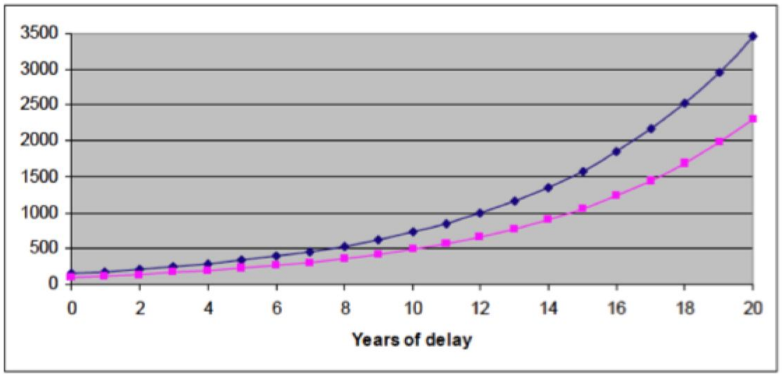
[12] Owens, B., An Economic Valuation of a Geothermal Production Tax Credit, NREL (2002)
[13] GeothermEx, Factors Affecting Costs of Geothermal Power Development (2005)
[14] AltaRock Presentation, Reno (2009).

Delay (years)	0	1	2	3	4	5	6	7	8	9	10
Exploration Costs	100	117	137	160	187	219	257	300	351	411	481
	150	176	205	240	281	329	385	450	527	616	721



Delay (years)	11	12	13	14	15	16	17	18	19	20
Exploration Costs	562	658	770	901	1054	1233	1443	1688	1975	2311
	844	987	1155	1351	1581	1850	2164	2532	2962	3466

Figure 11.7 Financial impact of delay on exploration costs. Source: GeothermEx (2004).

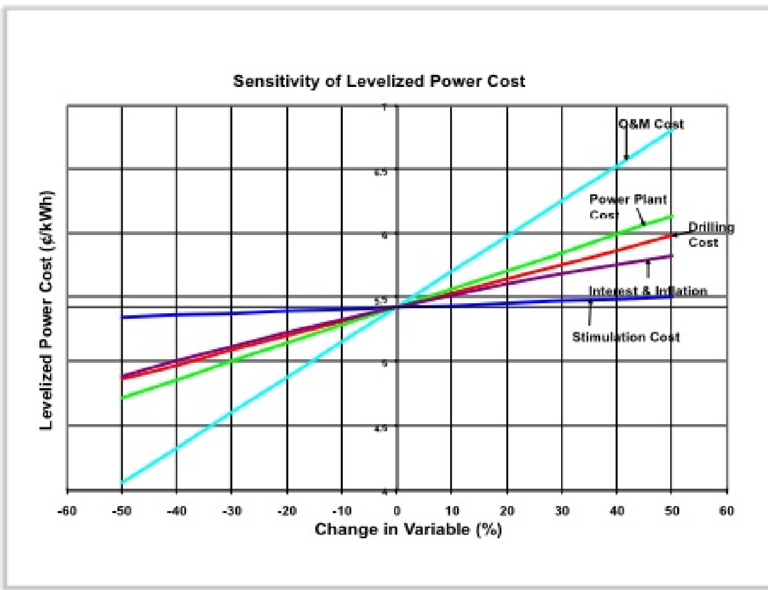


Figure 11.8 Sensitivity of levelized power cost. Source: AltaRock (2009), US DOE (2009), MIT (2006)

11.5.2 Cost of Technology

The cost of surface conversion technology is not generally available in reference literature, and typically is developed on a site-by-site or project-by-project basis. It is generally accepted, however, that there is an overall economy of scale that can be achieved by planning plant capacity to meet system demands (as a function of reservoir capacity, heat available and depth) to a maximum per site, will be approximately 160 MW per installation. This generalized relationship is illustrated in Figure 11.9.

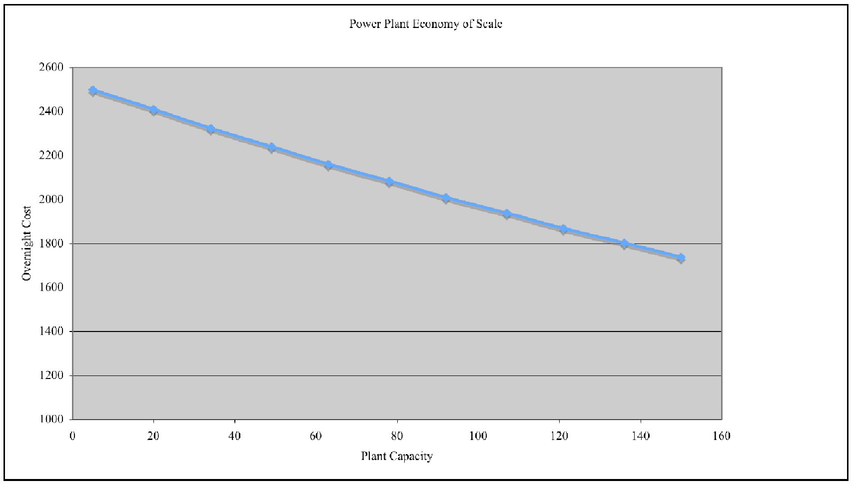


Figure 11.9 Power plant economy of scale. Source: NREL (2010).

Assuming 50 MW units for comparison, we expect the cost in terms of power output to be approximately:

- Binary $92/MWh
- Dual Flash $88/MWh

Financing new plant development in terms of principal and interest payments should average approximately 65 % of total costs, with the balance in operations costs. By comparison, this is typically reversed for a gas technology such as combined cycle gas turbine (CCGT) where capital costs should total approximately 22 % and fuels approximately 67 %. A summary of these assumptions regarding the development of surface plant facilities are shown in Table 11.9 below.

Table 11.9 Summary Assumptions for Surface Plant Facilities

Capacity Factor Assumed	Average 91%
Well Productivity Annual decline	4%
Fixed O&M costs	$75/kWy (in $US)
Power Plant Share	57%
Field, O&M, rework	33%
Make-up Well	8%
Injection Well	2%
Variable O&M	5% of Fixed O&M
Royalties (highly variable)	3% of Electric Revenue Sales
Average Wholesale Electric Cost	0.43/kWh
Accelerated Depreciation Period	5 years
Economic Lifespan of Facility	25 years
Typical Financing	Assumed at 2:1 or 67% debt
Cost of Equity	Assumed at 16%

11.5.3 Market and Returns

The electricity investment market rewards projects that are deemed stable, repeatable and competitive. In this arena there is a preference for projects that involve or distribute the risk among investment groups as well as the operating companies. An example to illustrate the cost of investment money among different groups will bear this out, showing clearly the preference for public vs. fully independent private investors.

Table 11.10 Levelized cost of capital investments expressed in ¢/kWh (2005 dollars)

Initial Capital Cost	Municipal Util.	Regulated IOU	GENCO	IPP
$2500/kW	1.99	2.85	3.20	3.76
$3000/kW	2.40	3.44	3.89	4.54
$3500/kW	2.81	4.06	4.54	5.33

IOU = Investor Owned Utility, GENCO= Generation Company, IPP = Independent Power Producer

Geothermal power is most closely tailored to the baseload energy market, where it can run at relatively constant rates with high capacity and availability factors. This characteristic means that long term PPA's (Power Purchase Agreements) can be developed or contracts for preferential dispatch into the electric system that reflects the dependable demand for this type of energy facility. When project financing is sought, it is reasonable to have in mind the type of characteristics that will be assumed as shown in Table 11.

Table 11.11 Critical market requirements for base-load dispatchable power

	2005	**2010**	**2015**	**2020**
Levelized Energy Cost (cents/kWh)	7-8	5-6	4-5	4
Risk				
Equity IRR*	15%	15%	15%	15%
Debt Interest Rate	8%	8%	8%	8%
Performance Warranty (years)	1	1	1	10
Preferred Technology Capacity Factor	30%	40%	50%	60%

11.5.4 Regulations and Policies

Large scale capital investments involved in the geothermal industry are subject to regulatory oversight on many levels, including water use, drilling permits and land use access and permission from local government. This is common for the permit and approval process that governs most power facilities requiring a siting and operating permit. Approvals, depending on the nature of the access required, may simultaneously involve local, provincial and in special circumstances, federal agencies.

The typical siting and permit process involves a series of hearings and fact finding which may include an environmental impact analysis. The time involved can range from approximately 14 months to 24 months, depending on complexity and the number of agencies involved.

Continued operation of current geothermal facilities can involve interaction and permits outside the scope of traditional permits for instance potential recharge of the reservoir with reclaimed wastewater. Siting such a pipeline and acquiring rights to the water from its source may involve several, potential overlapping jurisdictions and added extra cost(s) to the overall resource acquisition expenses.

11.5.4a Taxation Policies

Government agencies have several methods available to tax energy facilities including a severance tax (in this case steam extracted and "severed" from the underground resource), land value taxation or taxes on the final product, in this case electricity or direct heat for heat exchange. In addition, there are tax relief opportunities such as tax credits, rebates or subsidies designed to promote industry expansion or efficient operation.

Example tax policies from the US, which could be favorably utilized by EGS technologies in the future include:

a. **renewable energy transmission preference policy**, this would provide preference to clean renewable power on existing interprovincial transmission lines, and potentially offset any imbalances in electric supply portfolios by securing transmission access for diverse renewable based generation

b. **creation of a pool of air emission credits -** as a non-polluting energy source, EGS could provide a source of air credits that could be traded or used to offset other technologies. For instance, credits could be made available for CO_2, SOx or NOx depending on location.

c. **other credits** - other credit sources are available which could offset some of the high initial capital costs of geothermal power development including:

business tax credits[15]

[15] An example of a business tax exemption is currently available in Hawaii. Known as the *High Technology Business Investment Tax Credit*

Through December 31, 2005, Hawaii offered a 100% tax credit on an equity investment in a qualified high tech business (QHTB). A "qualified high tech business" is defined as a business that conducts more than 50% of its activities in non-fossil fuel energy-related technology. Eligible technologies include geothermal heat pumps.

This credit applied to the industrial sector. It was issued over a five-year period with a maximum limit of $2 million dollars. Specifically, the credit was allocated as follows: 35 % in the year the investment was made (maximum credit of $700,000) · 25% in the first year following the year in which the investment was made (maximum credit of $500,000) · 20% in the second year following the investment (maximum credit of $400,000) · 10% in the third and fourth years following the investment (maximum credit of $200,000) property tax exemptions

sales tax exemptions (for major structural or operating purchases)

exemptions on public utility taxes

11.5.4b Royalties, Payments and Leases

On federal lands, limited exploration may be conducted before securing a lease upon approval by the appropriate permitting authority. Typically, development operators pay federal and provincial income tax on the profits of their operations in a fee similar to a severance tax. In addition, there may be a property tax on the value of the geothermal resource in the reservoir, and local property taxes can be imposed on the value of surface installations and power plants.

11.5.4c Market Subsidies

Most renewable energy technologies are not directly competitive with fossil based power generation in current markets. This is a function of production costs, location and access and the capacity factor implied by intermittency of some resources such as wind and solar energy. To overcome this, many institutions have adopted a series of incentive mechanisms to help these technologies become established in current markets. Success is a function of timing, management and implementation policies as well as the level of competition in the market. Since it is impossible to generalize about any given support system, we have simply listed the system and its capabilities below.

- **Renewable Portfolio Standard (RPS)** - this system sets a percentage or MW goal for purchase by individual utilities within a given market area. Since each utility must respond by purchasing a proportionate amount of renewable power, the market incents the development of new, competitive technologies.

- **Market based development systems** - Systems such as the original Renewable Energy Investment Plan in California provide targeted incentives for competitive technologies through auctions or in other bid or performance programs. The objective is to provide short-term help to ensure the technologies become competitive within the bid market.

- **Performance based payments** - this system pays a stipend to renewable energy producers to cover the gap between market price and the producers marginal cost of production.

- **Capital loans or subsidies** - this system effectively acts as a loan guarantee, backing up the financing commitment of lenders for the capital facilities including high risk drilling or expansion into areas not well defined by the current industry.

11.5.4d Voltage and VARS Support

A unique aspect of AC power systems is the need to provide minimum voltage support through the system, a role typically undertaken by baseload power generators. Of equal value is the reactive power needed by the system or VARS (volt-ampere reactive power). Because of its low operating costs, coupled with high reliability and capacity factors, EGS is in a position to help underpin the need for these two roles. It is difficult to separate a charge, either direct or through a systems-benefit charge, which can be captured to pay for this background power management need. Options exist, however, that could make the use of EGS more competitive in this role. The first would be to forgive a system uplink charge in favor of VARS or voltage support and the second is to offer a subsidy equal to the benefit received through the life of the facility.

11.5.4e Power Purchase Agreements

In general, a Power Purchase Agreement (PPA) is a legal contract between a generator and a power buyer. Contracts may last anywhere between 15 and 20 years, although 10 years is a common period for merchant contracts. During the contract period, the power purchaser buys energy (which could include capacity and/or ancillary services), from the seller. These agreements are often critical considerations in the financing plans for independently owned electricity generating assets. Here the PPA is typically reached between an independent power producer, or "IPP" and a dispatch agency such as an ISO.

Electricity rates are typically agreed upon as the basis for the PPA. Prices may be flat, escalate over time, or be negotiated in any other way as long as both parties agree to the negotiation. The PPA typically specifies energy volumes over time is expected, and assigns a penalty for non-achievement. This system ensures that power generation from a preferred source is incented for the seller to competitively provide power from a source such as renewable generation over a given period of time[16].

These sales and contracts are typically entered into by a private entity selling to a public power distributor, public or investor-owned utility

11.6 ENVIRONMENTAL ISSUES AND ALTERNATIVE MARKETS

All government institutions require that developers submit exploration and development plans. All permits to conduct exploration activities and for construction of facilities require a thorough environmental review before the permit may be granted. Access to private land can be obtained by sale, lease, permit, option or any other mutual agreement with the owner of the surface property and geothermal estate.

Geothermal development on crown or privately owned land usually requires a series of permits from provincial or local agencies for road and pipeline construction, water and sewage disposal, air emissions and solid waste disposal.

Renewable resources such as EGS offer attractive power market contributions beyond power generation, as suggested by the preceding section. In addition, they have environmental quality characteristics that make them desirable (Chapter 10). In the case of negative environmental effects that must be taken into account, EGS like any other power generator has a land footprint for generation and power transmission. This facility must have support roads, pumping stations, surface piping and manifolds and substation transformers. In scale, and in comparison to fossil-

[16] For a brief description of geothermal PPA's see: http://www.nacleanenergy.com/index.php?option=com_content&view=article&id=1477:brief-anatomy-of-a-geothermal-power-purchase-agreement

fuel generation technology the footprint of operations is less than 1/2. The only fuel use is initial pressurization and periodic replacement of fluids for heat transfer.

EGS facilities have the potential to provide an attribute benefit to the environmental quality markets in the form of potential credits that can be traded on "green" markets, or for offsets in markets that seek to meet Kyoto-type goals. Since it operates as clean baseload power, EGS generates net positive benefits that have value directly proportional to the amount of power generated. Given current permitting and relicensing delays for nuclear plants, combined with expected retirement for many older coal generating plants which may not be able to meet environmental standards, hydrothermal as well as EGS generation is likely to prove to be a cost effective alternative. Long-term carbon credits can be developed in these instances to act not only as the standard but as a tradable and bankable commodity for domestic and international exchange.

11.7 CONCLUSIONS

Geothermal installations are important not only in terms of achieving redundancy in power systems, but also in terms of their displacement potential for other more costly and potentially environmentally damaging technologies.

Costs for these installations, at a range of application from near surface heat exchange to deep-engineered systems, have been falling and becoming more competitive over time. There are limits to the usefulness and deployment, not only from geographical location, but also from the nature of the technology chosen for power development and exchange.

However, in the main, these systems are capable of deployment in a very wide range of circumstances where their contribution is competitive in power generation, heat exchange (energy efficiency) and ultimately carbon credit and valuation.

There are, ultimately, a range of risks and obstacles for the future development of both hydrothermal and EGS facilities.

- **Continuing public debate over changes in land-use**

  This is true, even when surface footprints are minimal, and is amplified over fears of water table infiltration, water reserve use and induced seismic risk

- **High Risk and Expensive Financing Charges**

  Due to locational impediments as well as perceived risks in new EGS exploration, investment in many geothermal projects remains low due to perceived high investment risks. The exploratory phases of a geothermal project are marked by not only high capital costs but also a significant chance of failure. The combination of high risk and high cost produces a "money gap" as banks generally refuse to finance such risky endeavors. Banks that do finance geothermal projects rarely offer interest rates below 15%.

- **Grid Access**

  Some of the most promising geothermal resources lie great distances from regions of large electricity consumption. The need to install adequate transmission capacity often deters investment in geothermal projects, thus impeding the development of this renewable energy. In 2002, MidAmerica Energy abandoned its geothermal project in near California's Salton Sea primarily due to lack of available transmission resources.

- **Need for Co-Funded Exploration Drilling Programs**

  Drilling presents the most significant area of risk and elimination of uncertainty. A risk reduction strategy would have the government sharing some of the costs associated with the risky exploratory stages of a geothermal project by co-funding exploration drilling. By lowering the cost of drilling, private firms would have more incentive to accept the risks associated with preliminary stages of a geothermal project. If a drilling venture proves successful, the firm repays the Federal Government. Unsuccessful wells, on the other hand, would not require repayment.

- **Geothermal Production Tax Credit (PTC)**

  Canada has no current production tax credit for geothermal facilities; in the US, the PTC has been extended through 2013. It is clear that a long-term geothermal production tax credit can provide significant benefits, particularly in reducing the uncertainty currently associated with public funding. The National Renewable Energy Lab found that a PTC of 1.8 cent/kWh would reduce the levelized cost of geothermal electricity by as much as 30%. The same report found that a geothermal PTC might eventually generate net revenues. Geothermal plants pay significantly higher taxes than more conventional power plants, meaning the expansion the tax base partially offsets the costs of expanding the geothermal industry.

- **Expanded Renewable Energy access to the Transmission Grid**

  Improving transmission corridors to areas with geothermal reservoirs would boost investment in geothermal energy. Such programs have been proposed for accessing the wind-rich regions.

12. SUMMARY AND RECOMMENDATIONS

12.1 INTRODUCTION

Based on the analyses in the proceeding chapters, a summary of high potential geothermal regions in Canada is presented here. The intent is to show on a national scale the broad distribution of geothermal resources based on final end usage. In addition, a series of recommendations on research required to help reduce barriers to development of these geothermal resources is presented.

12.2 HIGH POTENTIAL GEOTHERMAL REGIONS OF CANADA

Geothermal energy potential is broadly distributed across Canada. How these resources may be used depends largely on temperatures that are accessible at reasonable drilling depth. Based on this, resource distribution is discussed in terms of end usage, high temperature electrical generation, binary system electrical generation, direct usage, and heat exchange systems.

12.2.1 High Temperature Electrical Potential

For electrical generation high temperature resources at reasonable drill depths are required. Figure 12.1 shows the depth to 150 °C, the temperature at which electrical generation potential becomes reasonable. As rocks tend to become too weak to maintain connected pore systems below 5 km, drilling and development costs are likely to become excessive for geothermal development based on current technology. We therefore define regions at 150 °C that are 5 km depth or shallower as having potential for high temperature geothermal systems (Fig. 12.2). In much of this region in NE British Columbia and the southern Northwest Territories these high temperatures are found in known porous sedimentary sequences. These regions have the highest potential for immediate development of geothermal energy given that the resources are already broadly defined by petroleum exploration drilling. In contrast high temperature regions from southern British Columbia are defined largely by extrapolation of shallow temperature profiles and the true heat resources is less certain. In addition this region is characterised by metamorphic and igneous rocks that typically have very low permeabilities, excepting near major fault structures that control thermal spring distribution (Grasby and Hutcheon, 2001). In defining high temperature resource we also include the volcanic belts of western British Columbia and Yukon. While there is little thermal gradient information, where known (e.g. the Garibaldi Belt) thermal gradients are elevated. Volcanic regions globally also have hosted some of the most important geothermal resources and are thus included here as having high resource potential.

12.2.2 Binary Electrical Systems/Direct Use

For resource temperatures below 150 °C electric generation is still possible through binary electrical generation systems (Chapter 2) down to temperatures as low as 80 °C. In addition, these resources lend themselves to direct use application (e.g. space heating). However, because of lower efficiencies of these systems, requirements for productive reservoirs are greater. The costs associated with enhancing reservoir permeability to produce lower temperature resources would most likely make such projects uneconomic. Therefore we define the potential for binary systems as those areas of sedimentary basins with known temperature resources between 80 and 150 °C (Fig. 12.3). In addition, the numerous thermal springs in western Canada also suggest areas of local high temperature resources. We include these as potential sites as well.

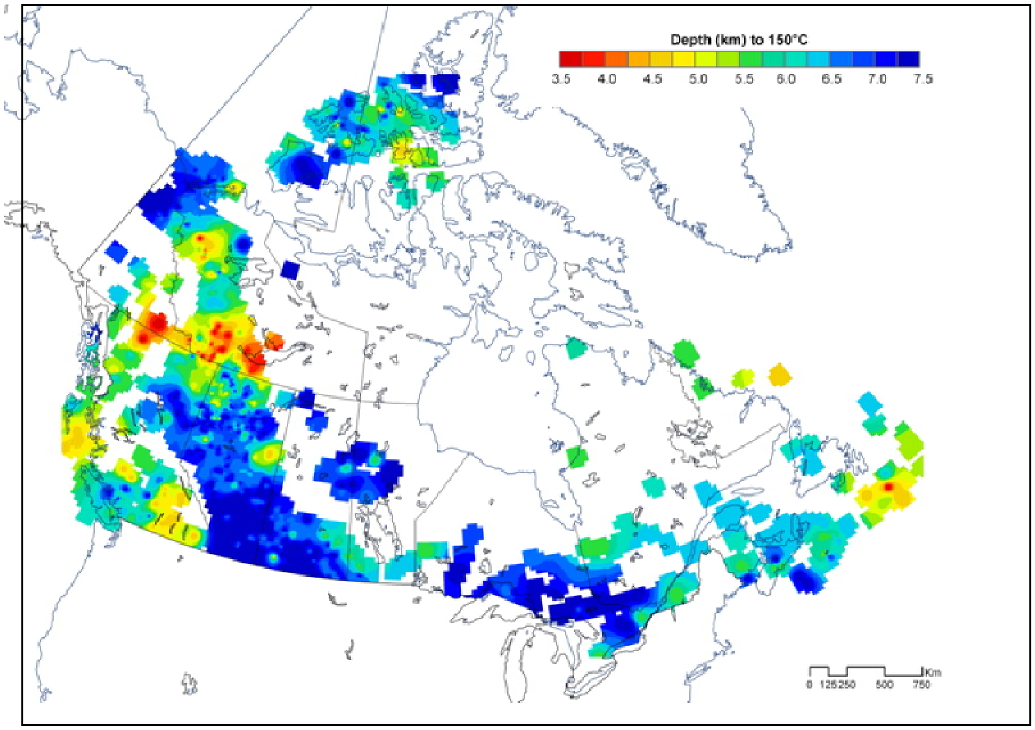


Figure 12.1. Map showing estimated depth to 150 °C across Canada.

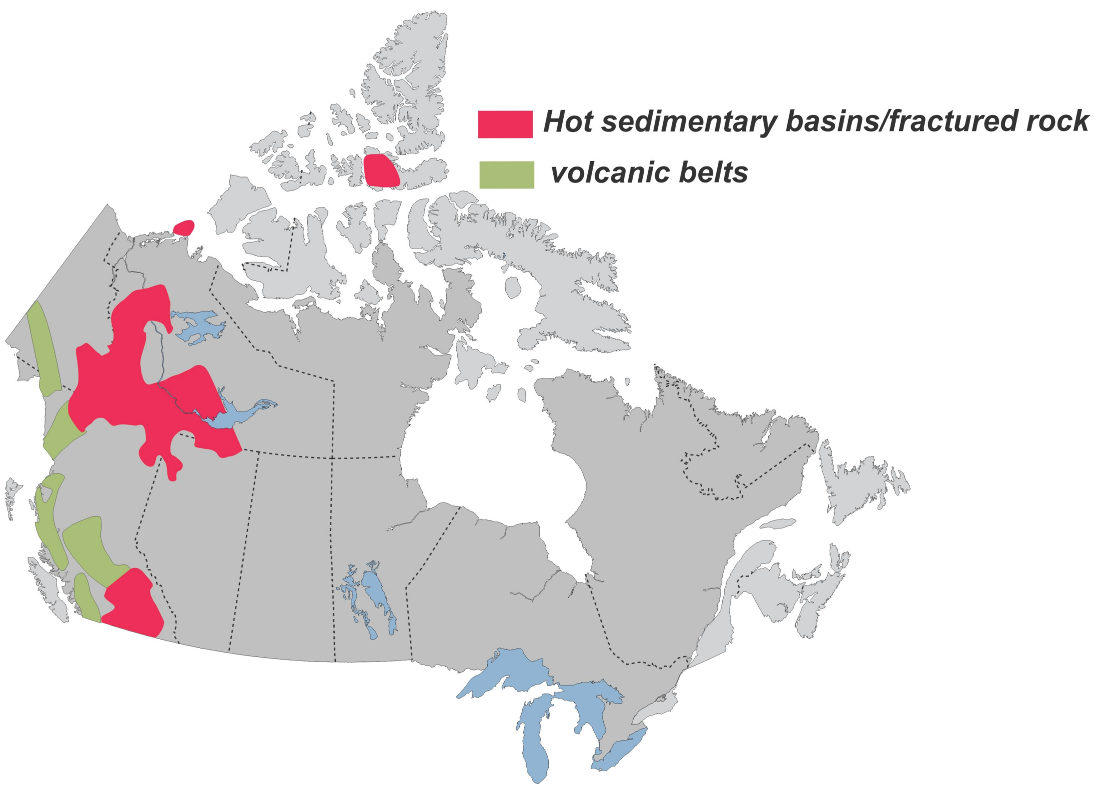


Figure 12.2. Map showing geographic distribution of high temperature regions (> 150 °C) that are within 5 km of ground surface.

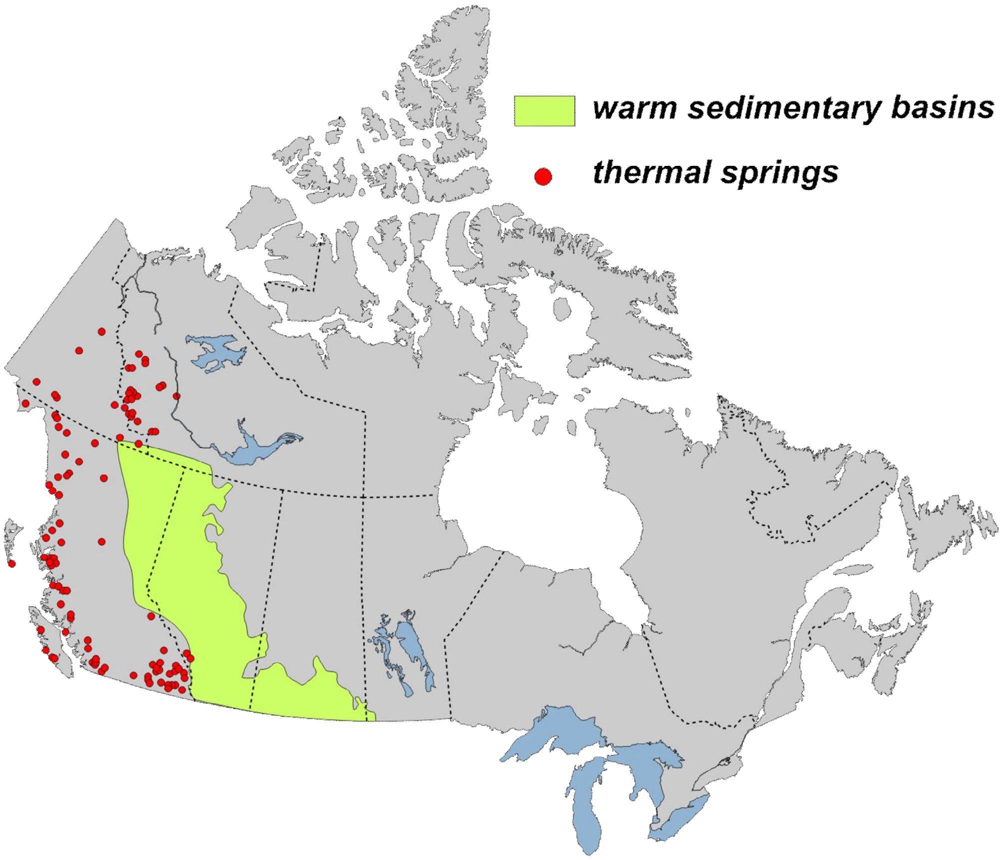


Figure 12.3. Map showing geographic distribution of sedimentary rocks with known temperatures between 80 and 150 °C suitable for binary geothermal power systems. Also, locations of known thermal springs in Canada which may indicate localised moderate to high temperature resources.

12.2.3 Heat Exchange

Effective use of heat exchange systems require shallow resources that can easily produce waters, or be easy to drill shallow well systems to install circulation loops. We define here the highest potential for heat exchange systems as the sedimentary basins of Canada which both have porous rock and/or typically thick glacial sediments. This is further divided into moderate and cool regions based on shallow temperature maps in Chapter 5 (Fig. 5.16). Highly fractured rocks of the deformed portions of the Canadian Cordillera can also enhance potential for permeability and thus effectiveness of heat exchange systems are also included here. While regions of the Canadian Shield do have localised potential associated with abandoned mines

(Chapter 6), in general costs of drilling and development in granitic and metamorphic rocks makes the Canadian Shield region lower potential.

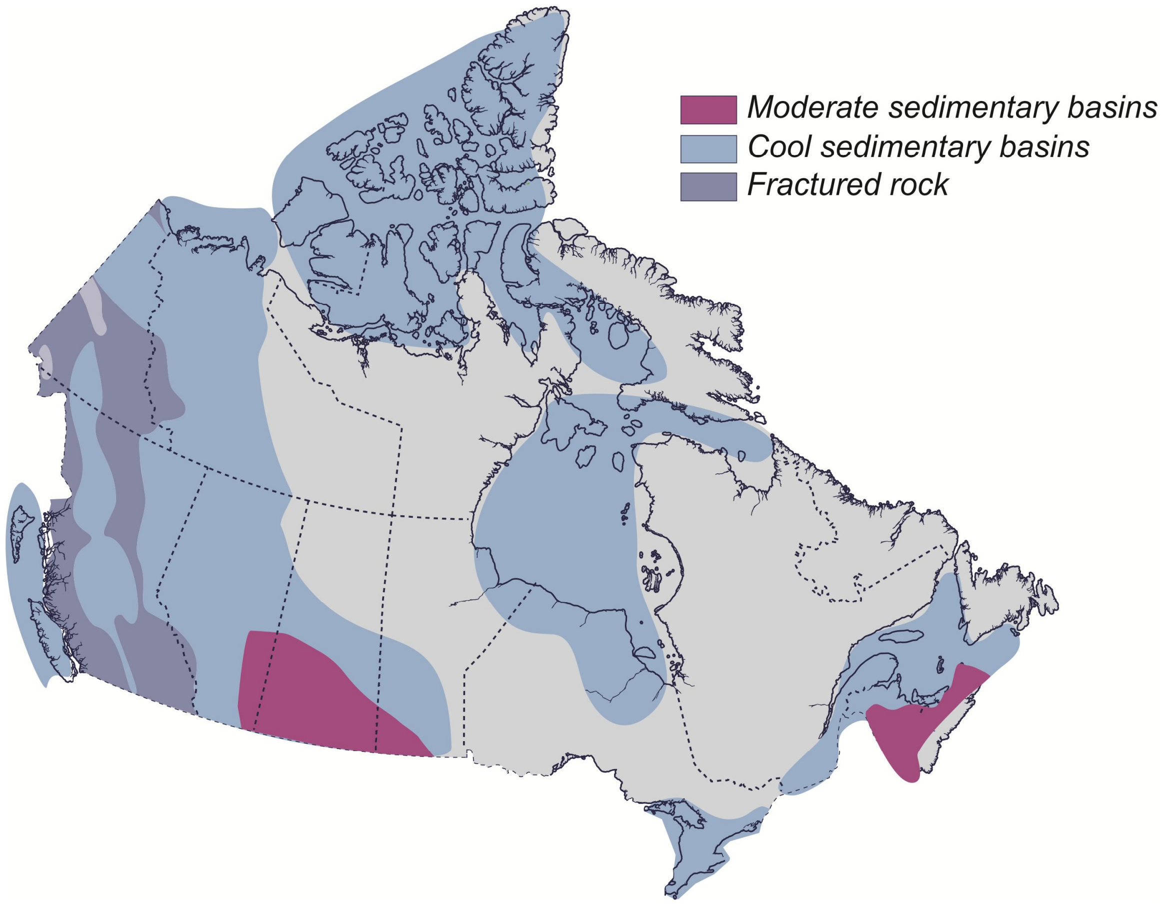


Figure 12.4. Map showing geographic regions considered to have higher potential for development of heat exchange systems in Canada.

12.2.4 National Geothermal Potential

Based on the proceeding discussion a map (Fig. 12.5), showing distribution of national resource potential, is presented. Resource potential is ranked from the most efficient end usage (high temperature electrical generation), to the least (heat exchange systems). For any region only the most efficient usage is illustrated, however, lower efficiency systems are typically feasible in the same region (e.g. direct use and heat exchange can also be applied in a region with potential for high temperature electrical generation). Highest potential regions for electrical generation are located in British Columbia, Yukon, NWT and northern Alberta. Where suitably located these systems could be connection to transmission lines, providing reliable and clean base load power to Canadians. In addition, there I significant potential to provide a domestic source of clean and renewable power production to remote northern communities in the Yukon and NWT (off grid local generation). While based on limited data, there is interesting potential for electrical generation in some High Arctic Communities (e.g. Resolute Bay). Further potential for binary system electrical generation, associated with warm sedimentary basins, exists through broad regions of western and northern Canada. Direct use potential is broadly distributed in regions of sedimentary basins across Canada, from coast to coast to coast. Abandoned mines as well have broad distribution, including areas of the Canadian Shield.

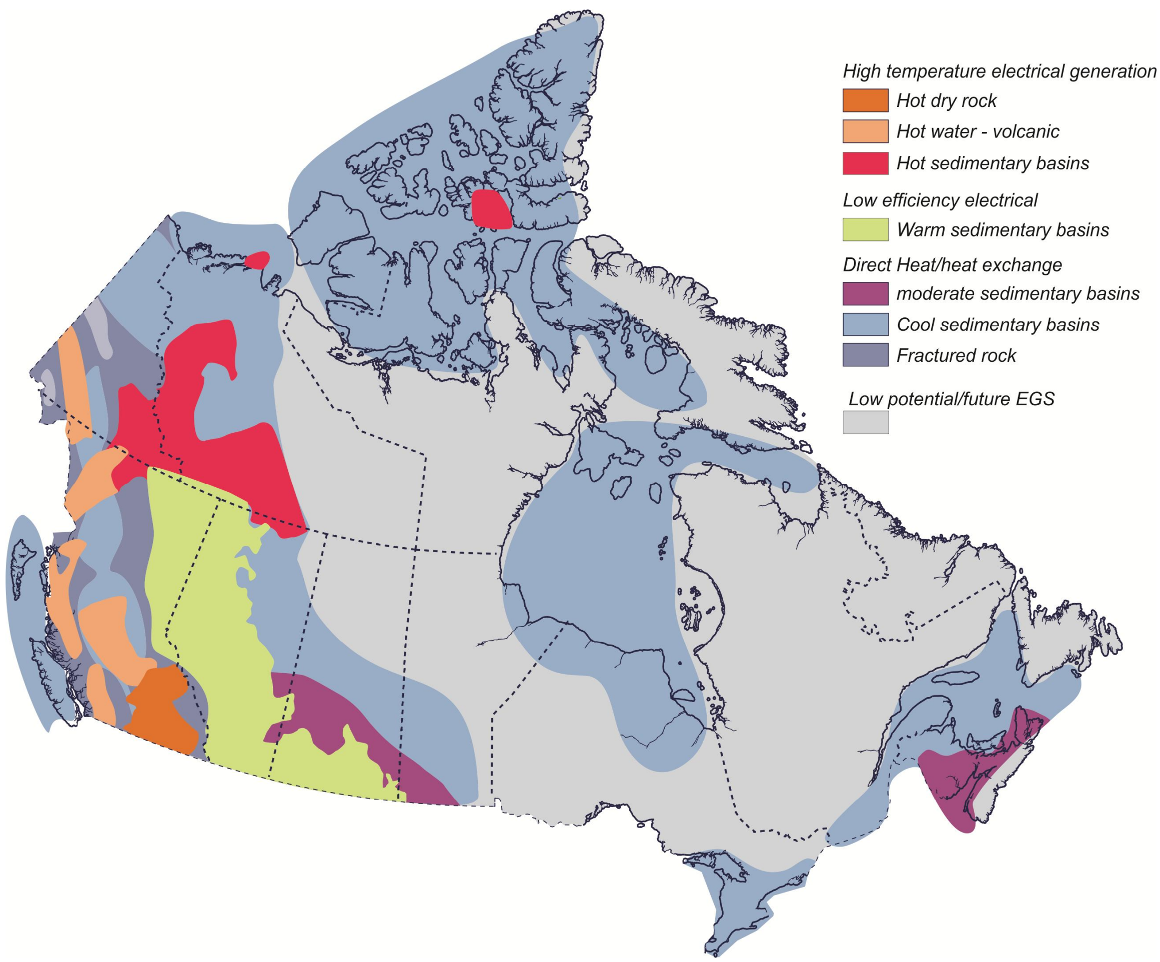


Figure 12.5. Map showing regional distribution of geothermal energy potential in Canada.

12.3 GEOSCIENCE RESEARCH PRIORITIES

There is enormous geothermal energy potential in Canada that has yet to be harnessed. To realise this potential there are several regulatory and policy barriers that need to be overcome which have been addressed elsewhere by organisations such as CANGEA. Here we highlight geoscience research required to: 1) reduce the geological risk in geothermal exploration, 2) enhance effectiveness of project design to maximize production, and 3) support regulatory development so that knowledge based resource management decisions can be made in order to maximize long term production of geothermal power. Main areas of research focus and identified outcomes are described below.

12.3.1 Regional Characterisation of Geothermal Properties

Only 40% of the Canadian Landmass has sufficient data to allow characterisation of the geothermal potential. Even then much of the data are limited. New data collection and digitization of existing data into a readily assessable database is required to help industry reduce exploration risk. This requires a significant effort at data compilation (several million temperature measurements are likely in existence). Large issues of data quality and effectively dealing with data volume need to be addressed. Once compiled and made readily available, significant value-added knowledge can be gained on regional temperature fields and geological controls on heat flow.

Compilation of existing data will allow more focused new data collection, including:

- Down hole temperature profiles
- Heat flow determinations
- Thermal conductivity determinations.
- Heat generation measurement

Outcomes:

Definition of high potential geothermal regions in Canada that will reduce exploration risk to levels competitive with other countries, spurring new industry investment in geothermal exploration in Canada

12.3.2 Hydrothermal Systems

Thermal springs are a key geothermal exploration tool (equivalent to a mineral showing). Canada has over 150 known thermal systems, most of which are poorly characterised (locations are uncertain, temperatures and geochemistry are poorly unknown). Industry requires geoscience data on spring occurrence, temperatures, and geochemistry to support exploration. In addition, more research on the hydrogeology of thermal spring systems can provide vital information on the crustal-scale circulation of fluids which may aid modelling of deep geothermal systems. As well, thermal springs support poorly characterised unique and rare ecosystems that could be impacted by geothermal development. Characterisation of these systems needs to be conducted to ensure preservation as part of any geothermal development.

Thermal spring research would include:

- Systematic documentation of thermal spring location, temperature and geochemistry
- Modelling of controls on spring hydrogeology
- Characterisation of rare ecosystems and species associated with spring sites

Outcomes:

Complete inventory of geothermal systems in Canada provides industry with critical data required to support exploration decisions. Geoscience data supports development of environmental permitting regulations.

12.3.3 Sedimentary Basins

Canada is covered by extensive sedimentary basins characterised by porous rock holding large volumes of fluids. For some regions these basins are already know to hold high temperature fluids suitable for electrical generation or warm fluids suitable for direct heating use. Further refinement of high priority target areas would aid exploration and development. In particular definition of key geological attributes (porosity, permeably, formation water salinity) that may affect economic development would support geothermal development. In addition, examination of co-development of carbon sequestration with geothermal systems (injected CO_2 can be a much more effective fluid than water for transporting heat energy) should be addressed. As multiple uses of sedimentary rock for both resource development and waste storage are being considered, appropriate management and regulatory frameworks need to be developed based on geoscience knowledge.

Sedimentary Basin research would address:

- Definition of high potential geothermal targets
- Geological factors that affect project economics
- Characterisation of sedimentary basins with limited knowledge base

Outcomes:

Delimitation of high potential hot aquifers help targeted regions suitable for electrical generation potential as well as direct heat. Also geoscience data aids regulatory development of pore-space management in areas of multiple use (CCS, oil/gas production, waste injection/storage).

12.3.4 Volcanic Belts

Volcanic systems in Canada are poorly characterised. Better definition of age distribution can define recent volcanic events and associated high temperature conditions.

Volcanic Belt research would address:

- Definition of high potential geothermal targets
- Geological factors that affect project economics
- Characterisation of sedimentary basins with limited knowledge base

Outcomes:

Definition of age distribution of volcanic rocks in Canada enables focused exploration for geothermal systems associated with young systems and helps refine resource potential.

12.3.5 Crustal Scale Hydrogeology

Geothermal developments involve movement of fluids through deep crustal rocks. Better understanding of the hydrogeological properties (porosity/permeability, etc.) is required to enable modelling of resource potential, production rates, and to regulate long-term sustainable resource development.

Crustal scale hydrogeology research would address:

- Modelling of crustal-scale flow
- Characterisation of regional stress fields
- Deep research wells for primary data collection

Outcomes:

Readily available data and crustal-scale models of deep fluid flow allow government agencies to better assess resource potential as well as to aid industry in making investment decisions.

12.3.6 Microseismicity

Enhanced geothermal system development requires injection of water and opening of permeable networks. Induced seismicity can be an inherent environmental impact. Research on appropriate injection systems based on new-knowledge of crustal hydrogeology is required.

- Research on regional stress regime to define areas of low potential for induced seismicity and to define best orientation for injection to minimize risk.
- Development of new and enhanced monitoring technology

Outcomes:

Geoscience data supports regulatory development on where most appropriate regions for EGS development in Canada are, as well as defining appropriate controls on injection pressures and engineering design.

12.3.7 Enhanced Geothermal Systems

EGS technology is developing and could provide a significant expansion of geothermal resource potential in Canada.

- More definition of EGS potential regions
- New data collection on heat generation in rock masses is required to define areas of ‘hot rock”
- Development of deep drilling technology

Outcomes:

Characterisation of EGS potential in Canada and definition of potential target areas for focused research efforts and potential demonstration projects.

12.3.8 Remote Sensing

Canada’s large land mass makes geothermal exploration inherently challenging. Development of new remote sensing technology can aid focused exploration.

- Thermal imaging
- Geophysical methodologies

Outcomes:

New research places Canada as a world leader in remote sensing technology in geothermal exploration.

12.3.9 Ground Source Heat Pumps

Ground source heat pump systems are one of the most efficient heating and cooling alternative available in Canada. Installation costs of associated ground heat exchangers are expensive however. Research to decrease installation costs and expand the market share of that technology is needed.

- Refine local-scale maps of subsurface temperature, heat flow and thermal conductivity to target geological settings in urban areas with better heat transfer properties

- Improve design methods to better asses system performances accounting for climatic and geological conditions that can prevail above and below the subsurface

- Develop new products or methods to improve heat transfer with the subsurface and reduce the length of ground heat exchangers

Outcomes:

Refined maps, improved design methods and new products are expected to help the geoexchange industry to compete with other heating and cooling technologies that use conventional energy such as fossil fuel. This can contribute to reduce green house gasses emissions and make Canada among the top countries for installed geoexchange capacity per capita.

12.3.10 Abandoned Mines

Abundant low-temperature geothermal resources are hosted by abandoned and active mines, which can reduce drilling and installation costs of ground-source heat pump systems. The inventory of mine sites across Canada is currently incomplete. The following features of mine site shall be inventoried in all provinces and territories:

- Underground mines

- Open pits and water retention ponds

- Exothermic mine waste storage facilities

Outcomes:

As current demonstrations projects moves toward completion, providing online inventories that are easily accessible to policy maker and business can trigger new projects across Canada to offer energy savings to end users.

REFERENCES

Acornley, R.M., 1999. Water temperature within spawning beds in two chalk streams and implications to salmonid egg development. Hydrologic Processes 13: 439-446.

Acres International Ltd., 1985. Moose Jaw geothermal study. Earth Phys. Br., Open File 85-7, 225pp.

Allen, A., Milenic D., and Sikora, P., 2003. Shallow gravel aquifers and the urban 'heat island' effect: a source of low enthalpy geothermal energy. Geothermics 32: 569-578, doi:10.1016/S0375-6505(03)00063-4.

Allen, D.M., 1997. Modelling protocol for successful simulations of flow and heat transport in ATES systems. In: Proceedings of the Stockton Geothermal Conference II, Stockton, N.J., March 16 & 17, 1997.

Allen, D.M., Woo, C., Shymko, G.F. and Maynard, S., 2000. Operating strategies for ATES in areas with non-ideal climates. In: Proceedings of the 8th International Conference on Thermal Energy Storage, Terrastock. Stuttgart, Germany, August 27- Sept 3, 2000.

Allen, D.M., Grasby, S.E., and Voormeij, D.A., 2006. Determining the circulation depth of thermal springs in the southern Rocky Mountain Trench, southeastern British Columbia, Canada using geothermometry and borehole temperature logs. Hydrogeology Journal, 14, 159-172.

Allis, R.G., 2000. Review of subsidence at Wairakei field, New Zealand. Geothermics 29: 455-478.

Allis, R.G. and Garland, G.D., 1979. Heat flow measurements under some lakes in the Superior Province of the Canadian Shield. Can.J.Earth Sci., 16, 1951-1964.

Andersen, S. O., 1975. "Environmental Impacts of Geothermal Resource Development on Commercial Agriculture: A Case Study of Land Use Conflict." Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, 20-29 May, 1975, San Francisco, pp. 1317-1327.

Andersson, O. and Sellberg, B., 1992. Swedish ATES applications: Ten years of development experience in aquifer thermal energy (heat and chill) storage. *In* Proceedings of the Intersociety Energy Conversion Engineering Conference, San Diego, California, August, 1992.

Arkay, K., 1992. Geothermal energy from abandoned mines: A methodology for an inventory, and inventory data for abandoned mines in Québec and Nova Scotia. Geological Survey of Canada, Open file report 3825, Calgary, 45 pp.

Armstead, C.H., 1975. "Summary of section V: Environmental Factors and Waste Disposal." Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, 20-29 May, 1975, San Francisco, pp.1313-1523.

Armstead, C.H., 1978. Geothermal Energy: Its Past, Present and Future Contributions to the Energy Needs of Man. John Wiley and Sons, New York, N.Y.

Armstrong, R.L., 1988. Mesozoic and early Cenozoic magmatic evolution of the Canadian Cordillera. *In* Processes in continental lithospheric deformation. *Edited by* S.P. Clark, C. Burchfiel, and J. Suppe. Geological Society of America Special Paper 218, pp. 55-91.

Arnold, S.C., 1984. Near-Surface Groundwater Responses to Injection of Geothermal Wastes. University of Idaho Technical Report to USDOE, DOE/ID/12210-T1.

ASHRAE, 2007. Geothermal Energy. In: ASHRAE (Editors), ASHRAE Handbook. Heating, ventilating, and air-conditioning applications. American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta, pp. 32.1-32.30.

Axtmann, R.C., 1975a. Environmental Impact of a Geothermal Power Plant. Science, Vol. 187 (4179: pp. 795-804)

Axtmann, R.C., 1975b. "Chemical Aspects of the Environmental Impact of Geothermal Power." *In* Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, May 20-29, 1975, San Francisco, pp. 1323-1327.

Babcock, E.A., 1978. Measurement of subsurface fractures from dipmeter logs. American Association of Petroleum Geologists Bulletin, v. 62, p. 1111-1126.

Bachu, S. and Burwash, R.A., 1994. Geothermal Regime in the Western Canadian Sedimentary Basin. *In* Geological Atlas of the Western Canada Sedimentary Basin, (Editors G. D. Mossop and I. Shetsen), Canadian Society of Petroleum Geologists and Alberta Research Council, p. 447-454.

Banks, D., 2009. Thermogeological assessment of open-loop well-doublet schemes: a review and synthesis of analytical approaches. Hydrogeology Journal doi: 10.1007/s10040-008-0427-6.

Banks, D., Younger, P.L., Arnesen, R.T., Iversen, E.R. and Banks, S.B., 1997. Mine-water chemistry: the good, the bad and the ugly. Environmental Geology, 32(3): 157-174.

Barbier, E., 2002. Geothermal energy technology and current status: An overview. Renewable and Sustainable Energy Reviews, 6: 3-65.

Barker C., 1996. Thermal modelling of petroleum generation: theory and applications. In: Developments in petroleum science, vol 45. Elsevier, Amsterdam, p 512.

Baujard, C., Karytsas, C., Kohl, T., Manzella, A. and Schulte, T. (ed), 2008. Best Practice Handbook for the development of unconventional geothermal resources with a focus on Enhanced Geothermal Systems, ENGINE Coordination Action (Enhanced Geothermal Innovative Network for Europe) http://engine.brgm.fr

Bazargan Sabet, B., Demollin, E. and Van Bergermeer, J.-J., 2008. Geothermal use of deep flooded mines. Proceedings of the Post-Mining Symposium, Nancy, 11 pp.

Beach, R.D.W., Jones, F.W. and Majorowicz, J.A., 1987. Heat flow and heat generation estimates for the Churchill basement of the Western Canadian Basin in Alberta, Canada. Geothermics, 16, 1-16

Beardsmore, G.R., 2001. Crustal Heat Flow: A Guide to Measurement and Modelling. Port Chester, NY, USA: Cambridge University Press, 2001.

Bell, J.S., 1996. In situ stresses in sedimentary rocks (Part 2): Applications of Stress Measurements. Geoscience Canada, v. 23, no. 3, p. 135-153.

Bell, J.S, and Bachu, S., 2004. In situ stress magnitude and orientation estimates for Cretaceous coal-bearing strata beneath the plains area of central and southern Alberta. Bulletin of Canadian Petroleum Geology, v.51, no. 1, p. 1-28.

Bell, J.S., and Gough, D.I., 1979. Northeast-southwest compressive stress in Alberta; evidence from oil wells, Earth and Planetary Science Letters, November 1979, Vol. 45, Issue 2, pp. 475-482.

Bell, J.S. and McLellan, P.J., 1995. Exploration and production implications of subsurface rock stresses in Western Canada. *In*: Proceedings of the Oil and Gas Forum '95 - Energy from Sediments. J.S. Bell, T.D. Bird, T.L. Hillier and P.L. Greener (eds.). Geological Survey of Canada, Open File 3058, p. 349-352.

Bell, J.S., Price, P.R. and McLellan, P.J., 1994. *In-situ* stress in the Western Canada Sedimentary Basin. *In*: Geological Atlas of the Western Canada Sedimentary Basin. G.D. Mossop and I. Shetsen (compilers). Canadian Society of Petroleum Geologists and the Alberta Research Council, Chapter 29, p. 439-446.

Berman, R.G., 1981. Differentiation of calc-alkaline magmas: evidence from the Coquihalla Volcanic Complex, British Columbia. Journal of Volcanology and Geothermal Research, 9, 151-179.

Bernier, M., 2000. A Review of the cylindrical heat source method for the design and analysis of vertical ground-coupled heat pump systems. Proceedings of the Fourth International Conference on Heat Pumps in Cold Climates Conference, Caneta Research Inc., Aylmer, 14 pp.

Bertani, R., 2002. Geothermal Power Generating Plant CO_2 Emission Survey. IGA News, http://www.geothermal-energy.org/documenti/IGA/newsletter/n49.pdf.

Bertani, R., 2005. World geothermal power generation in the period 2001-2005. Geothermics 34: 651-690.

Bevier, M.L., 1983. Implications of chemical and isotopic compositions for petrogenesis of Chilcotin group basalts, British Columbia. Canadian Journal of Earth Sciences, 20, 515-524.

Bevier, M.L., Armstrong, R.L. and Souther, J.G., 1979. Miocene peralkaline volcanism in west-central British Columbia – its temporal and plate tectonics setting. Geology, 7, 389-392.

BGR , 2008. Hot Dry Rock, http://www.geozentrum hannover.de/nn_334982/EN/Themen/Energie/Projekte/Geothermie/Soultz_en.html

Blackwell, D.D., 2006. Assessment of the enhanced geothermal system resource base of the United States. Natural Resources Research [New York, N.Y.], Vol. 15, Issue 4, pp.283-308.

Blackwell, D.D. and Richards. M., 2004. Geothermal Map of North America. Amer. Assoc. Petroleum Geologists, Tulsa, Oklahoma, 1 sheet, scale 1:6,500,000.

Blackwell, D.D., Negraru, P. T., and Richards, M.C., 2007. Assessment of the enhanced geothermal system resource base of the United States. Nat. Resour. Res. 15, 283–308 doi:10.1007/s11053-007-9028-7.

Bloomfield, K.K. and J.N. Moore, 1999. Geothermal Electrical Production CO_2 Emissions Study. Geothermal Resource Council 1999 Annual Meeting October 17, 1999 – October 20, 1999, pp.1-5. Idaho National Engineering and Environmental Laboratory.

Blum, P., Campillo, G., Münch, W. and Kölbel, T. 2010. CO_2 savings of ground source heat pump systems - A regional analysis. Renewable Energy 35: 122-127.

Boothroyd, I.K.G., 2008. Ecological characteristics and management of geothermal systems of the Taupo Volcanic Zone, New Zealand. Geothermics 38: 200-209.

Bowen, R.G., 1973. “Environmental Impact of Geothermal Development.” Geothermal Energy, pp. 197-215, edited by P.F. Kruger and C. Otte, Stanford University Press, Ca.

BP 2006. Quantifying Energy, BP Statistical Review of World Energy, June 2006.

Bredehoeft, J., 2002. The Water Budget Myth Revisted: Why Hydrogeologists Model, Ground Water 40: 340-245.

Bredehoeft, J.D. , Wolff, R.G., Keys, W.S., and Shuter, E., 1976. Hydraulic fracturing to determine the regional in situ stress field, Piceance Basin, Colorado, Source: Geological Society of America Bulletin, February 1976, Vol. 87, Issue 2, pp. 250-258.

Bredehoeft, J., Papadopulos, S.S. and Cooper Jr., H.H., 1982. Groundwater: The Water-Budget Myth. *In* Scientific Basis of Water Resource Management, Studies in Geophysics, Washington, DC, National Academy Press, pp. 51-57.

Bridger, D.W. and Allen, D.M., 2005. Designing aquifer thermal energy storage (ATES) systems. ASHRAE Journal, September, S32-S38.

Bridger, D.W. and Allen, D.M., 2010. Heat Transport Simulations in a Heterogeneous Aquifer Used for Aquifer Thermal Energy Storage (ATES). Canadian Geotechnical Journal, 47 (1), pp. 96-115.

BC MSRM (British Columbia Ministry of Sustainable Resource Management), 2002. Rare Dragonflies of British Columbia.

Brock, T.D., 1975. “Predicting the Ecological Consequences of Thermal Pollution from Observations on Geothermal Habitats.” Environmental Effect of Cooling Systems at Nuclear Power Plants Symposium, August 26-30, 1974, Oslo, Norway, pp.599-622, Atomic Energy Agency, Vienna, Austria, (1975).

Bromley, C., 2003. “Practical methods of minimizing or mitigating environmental effects from integrated geothermal developments; recent examples from New Zealand.” In: Proceedings of the International Geothermal Conference, Multiple Integrated Use of Geothermal Resources, September 14–17, Reykjavik, Iceland, pp. 26-32.

Brown, A. Sutherland, 1969. Aiyansh lava flow, British Columbia. Canadian Journal of Earth Sciences, 6, 1460-1468.

Budinski, K.G. and Budinski, M.K., 2005. Engineering materials: properties and selection. Prentice Hall, Upper Saddle River, NJ, 855 pp.

Burns, B. and Leathwick, J., 1995. Geothermal Vegetation Dynamics. Part I: Map of the geothermal vegetation of the Te Kopia Scenic Reserve. Part II: Plant species organisation along major environmental gradients. Science for Conservation: 18. 26 p.

Burwash, R. A. and Burwash, R. W., 1989. A radioactive heat generation map for the subsurface Precambrian of Alberta. GSC Current Research C Paper 89-1C, p. 363–368.

Bustin, R. M., 1991. Organic maturity in the Western Canada sedimentary basin, International Journal of Coal Geology, Vol. 19, Issue 1-4m pp. 319-358.

CADDET energy efficiency, 1992. Geothermal mine water as energy source for heat pump. Available on the Internet: http://oee.nrcan.gc.ca/publications/infosource/pub/ici/caddet/english/pdf/R122.pdf.

Cameli, G.M. and Carabelli, E., 1975. "Seismic Control During a Reinjection Experiment in the Viterbo Region (Central Italy)." Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, May 20-29, 1975, San Francisco, pp. 1329-1334.

CGC (Canadian GeoExchange Coalition), 2009. A Buyer's Guide for Residential Ground Source Heat Pump Systems.

Canadian Standards Association, 2002. Design and Installation of Earth Energy. CSA-C448 Series 02.

CCOHS (Canadian Centre for Occupational Health and Safety), 2003. "4-Working Safely with Carbon Dioxide Gas." Retrieved July, 2010. http://www.msds.org/oshanswers/chemicals/chem_profiles/carbon_dioxide/working_cd.html

Chorney, R.J. and Sherwood, R.L., 1981. Geothermal Electric Energy and Its Impacts on the Environment- Regional Program Report: 81-05. Department of Environment, Environmental Protection Service, Pacific and Yukon Region.

Clague, J.J., Evans, S.G., Rampton, V.N., and Woodsworth, G.J., 1995. Improved age estimates for the White River and bridge River tephras, western Canada. Canadian Journal of Earth Sciences, 32, 1172-1179.

Clauser, C., 2006. Geothermal energy Landolt-B¨ornstein, Group VIII: Advanced Materials and Technologies, Vol. 3: Energy Technologies, Subvol. C: Renewable Energies ed K Heinloth (Berlin: Springer) pp 493–604.

Coney, P.J., Jones, D.L., and Monger, J.W.H., 1980. Cordilleran suspect terranes. Nature, 288: 329-333.

Cordell, L., Phillips, J.D., and Godson, R.H., 1992. Potential – field geophysical software version 2.0. *Dep. Int. U.S. Geol. Surv. Open File Report* 92-18.

COSEWIC (Committee on the Status of Endangered Wildlife in Canada). Retrieved March 15, 2010. http://www.cosewic.gc.ca/eng/sct4/result_e.cfm> Last Updated November, 15, 2006.

Cox, J.W., 1983. Long axis orientation in elongated boreholes and correlation with rock stress data. Paper J, Proceedings of the 24th Annual Logging Symposium, Society of Professional Log Analysts, Calgary, June 27-30, 1983.

Curry, R.A., Noakes, L.G. and Morgan, G.E., 1995. Ground water and the incubation and emergence of brook trout (*Salvelinus fontinalis*). Canadian Journal of Fisheries and Aquatic Sciences 52: 1741–1749.

Deichmann, N., Mai, M, Bethmann, F. and others, 2007. Seismicity Induced by Water Injection for Geothermal Reservoir Stimulation 5 km Below the City of Basel, Switzerland, American Geophysical Union, http://adsabs.harvard.edu/abs/2007AGUFM.V53F..08D

DiPippo, R., 2004. Second Law assessment of binary plants generating power from low temperature geothermal fluids. Geothermics 33, 565-586.

DiPippo, R., 2005. Geothermal Power Plants Principles, Applications and Case Studies. Elsevier Science.

DOE (United States Department of Energy). Retrieved November, 2009. http://www1.eere.energy.gov/geothermal/geopower_landuse.html

Duchane, D.V., 1996. Geothermal energy from hot dry rock: A renewable energy technology moving towards practical implementation . Renewable Energy, 9(1-4): 1246-1249.

Dunn, J.C., 1988. Research to tap the crustal magma source. Proc. Geothermal Program Review VI, "Beyond goals and objectives", April 19–21, 1988, San Francisco, California: 151–153.

Drury, M.J., 1986. Thermal conductivity, thermal diffusivity, density and porosity of crystalline rocks. Earth Physics Br., Open File 86-5, 52pp

Drury, M., 1988. Tectonothermics of the North American Great Plains basement: Tectonophysics, v. 148, p. 299–307.

Eaton, B.A., 1990. U.S. gulf coast geopressured-geothermal, Proceedings of the 12th New Zealand Geothermal Workshop, University of Auckland, Auckland, New Zealand (1990), pp. 273–279.

Edwards, B.R., and Russell, J.K., 1999. Northern Cordilleran volcanic province: A northern Basin and Range? Geology, 27, 243-246.

Edwards, B.R., and Russell, J.K., 2000. Distribution, nature, and origin of Neogene-Quaternary magmatism in the Northern Cordilleran volcanic province, Canada. Geological Society of America Bulletin, 112, no. 8, 2-17.

Edwards, L.M., G.V. Chilingar, H.H. Rieke III, and Fertl, W.H., Eds., 1982. Handbook of Geothermal Energy, Gulf Publishing Co., Houston, 83pp.

Elíasson, E. and Björnsson, O., 2003. Multiple integrated applications for low- to medium-temperature geothermal resources in Iceland. Geothermics, 32: 439-450.

Emerging Energy Research, 2009. Global Geothermal Markets and Strategies: 2009-2020.

Energy Resources Conservation Board (ERBC), 2010. Government of Alberta, Serial Publication ST45, Coal Mine Atlas Operating and Abandoned Coal Mines in Alberta

Environment Canada, 2008. www.ec.gc.ca/soer-ree/English/Indicators/Isuues/Energy/Bulletin/ ecind1 e.cfm

Ferguson, G., 2007. Heterogeneity and Thermal Modeling of Ground Water. Ground Water doi: 10.1111/j.1745-6584.2007.00323.x.

Ferguson, G., 2009. Unfinished Business in Geothermal Energy. Ground Water 47:167, DOI:10.1111/j.1745-6584.2008.00528.x

Ferguson, G. and Woodbury, A., 2003. Observed thermal pollution and post-development simulations of low-temperature geothermal systems in Winnipeg, Canada. Hydrogeology Journal, 14: 1206-1215.

Ferguson, G. and Woodbury, A.D., 2004. Subsurface Heat Flow in an Urban Environment. Journal of Geophysical Research 109, B02402, doi:10.1029/2003JB002715.

Ferguson, G. and Woodbury, A.D., 2005. Thermal sustainability of groundwater source cooling in Winnipeg, Manitoba. Canadian Geotechnical Journal, v. 42, p. 1290-1301.

Ferguson, G. and Underwood, E., 2006. Geochemical Effects of Thermal Development of Groundwater Resources: Modeling Results for Selected Samples from the Carbonate Rock Aquifer, Manitoba. St. Francis Xavier University, Antigonish, NS.

Ferguson, G.A. and Woodbury, A.D., 2007. Thermal Use of Groundwater and Source Water Protection. 35th IAH Congress, Lisbon, Portugal, Sept. 2007.

Ferguson, G., Grasby, S.E., and Hindle, S., 2009. What do aqueous geothermometers really tell us? Geofluids, 9, 39-48.

Florides, G. and Kalogirou, S., 2007. Ground heat exchangers - A review of systems, models and applications. Renewable Energy, 32(15): 2461-2478.

Fordjor, C. K., Bell, J. S. and Gough, D. I., 1983. Breakouts in Alberta and stress in the North American plate. Canadian Journal of Earth Sciences, v. 20, p. 1445-1455.

Forster, C., and Smith L., 1988a. Groundwater flow systems in mountainous terrain 1. Numerical modeling technique. Water Resource Research, 24: 999-1010.

Forster, C., and Smith L., 1988b. Groundwater flow systems in mountainous terrain 2. Controlling factors. Water Resource Research, 24: 1011-1023.

Fridleifsson, I., 2001. Geothermal energy for the benefit of the people. Renewable and Sustainable Energy Reviews, 5: 299-312.

Fry, V.A., 2009. Lessons from London: regulation of open-loop ground source heat pumps in central London. Quarterly Journal of Engineering Geology and Hydrogeology 42: 325-334.

Gabrielse, H., 1985. Major dextral transcurrent displacements along the northern Rocky Mountain trench and related lineaments in north-central British Columbia. Geological Society of America Bulletin, 96: 1-14.

Gabrielse, H. and Yorath, C.J., 1991. Geology of the Cordilleran Orogen in Canada. Geological Survey of Canada, Geology of Canada Series, v. 4 (Geological Society of America, Geology of North America, v G-2).

Gallup, D.L., 2009. Production engineering in geothermal technology: A review. Geothermics 38: 326-334.

GEO 2000 http://www.geography.info/planet_earth/20/earth_interior.html

Geothermal Heat Pump Consortium, 1997. Municipal building, Park Hills, Missouri. Available on the Internet: http://www.geoexchange.org/pdf/cs-064.pdf.

Geotop, The Quebec inter-university network for advanced studies and research in geoscience, Geothermal Data. http://www.geotop.ca/

Geotop, 2009. Data Geothermal http://www.unites.uqam.ca/geotop/geophysique/flux/data.htm

Ghomshei, M.M., 2007. Geothermal energy from Con Mine for heating the City of Yellowknife, NWT: A concept study. Available on the Internet: http://www.yellowknife.ca/shared/assets/Geothermal_Study_Final_Report6259.pdf.

Ghomshei, M.M. and Meech, J.A., 2003. Usable heat from mine waters : coproduction of energy and minerals from "mother earth". Proceedings of the 4th IPMM Conference, Sendai, 8 pp.

Ghomshei, M.M. and Sadler-Brown, T., 1996. Direct Use Energy from the hotsprings and subsurface geothermal resources of British Columbia, Canadian Geothermal Energy Association, BTech Publishers, Richmond, BC.

Giardini, D., 2009. Geothermal quake risk must be faced. Nature 462: 848-849.

Gipe, P., 1995. Wind energy comes of age. John Wiley& Sons Inc., pp.539.

Goldscheider, N. and Bechtel, T.D., 2009. The housing crisis from underground – damage to a historic town by geothermal drillings through anhydrite, Staufen, Germany. Hydrogeology Journal 17: 491-493.

Gorrell, H.A., 1984. Applications of existing data to low temperature geothermal exploration. Proc ENERGEX ‘84, ed. Curtis,F.A., Univ Regina.

Gough, D. I. and Bell, J. S., 1982. Stress orientations from borehole wall fractures with examples from Colorado, East Texas, and northern Canada, Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre, July 1982, Vol. 19, Issue 7, pp. 1358-1370.

Gough, D. I., Fordjor, C. K. and Bell, J. S., 1983. A stress province boundary and tractions on the North American plate. Nature, v. 305, p. 619-621.

Government of British Columbia, Ministry of Energy, Mines and Petroleum Resources, Historic Mines of British Columbia, Open file 2003-3 (Excel Table of Historic Mines), available on the Internet: http://www.em.gov.bc.ca/Mining/Geolsurv/Publications/OpenFiles/OF2003-03/toc.htm

Grasby, S.E., and Hutcheon, I., 2001. Controls on the distribution of thermal springs in southern Alberta and British Columbia. Canadian Journal of Earth Sciences, 38, 427-440.

Grasby, S.E. and Lepitzki, D.A.W., 2002. Physical and chemical properties of the Sulphur Mountain thermal springs, Banff National Park, and implications for endangered snails. Canadian Journal of Earth Sciences, 39, 1349-1361.

Grasby, S.E., Hutcheon. I., and Krouse, H.R., 2000. Influence of water-rock interaction on the chemistry of thermal springs in western Canada. Applied Geochemistry, 15: 439-454.

Grasby, S.E., van Everdingen, R.O., Bednarski, J., and Lepitzki, D.A.W., 2003. Travertine mounds of the Cave and Basin National Historic Site, Banff National Park. *Canadian Journal of Earth Sciences*, 40, 1501-1513.

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

Grayston, L.D., Sherwin, D.F. and Allan, J.F., 1964. Chapter 5, Middle Devonian. *In* Geological History of Western Canada, (Editors: R. G. McCrossan amd R. P. Glaister), Alberta Society of Petroleum Geologists, p. 49-59.

Green, N.L., Armstrong, R.L., Harakal, J.E., Souther, J.G. and Read, P.B., 1988. Eruptive history and K-Ar geochronology of the late Cenozoic Garibaldi volcanic belt, southwestern British Columbia. Geological Society of America Bulletin, 100, 563-579.

Gundmundsson, J.S. and Bott, T.R., 1979. Deposition of silica from geothermal waters on heat transfer surfaces. Desalination, 28: 125-145.

Haehnlein, S., Grathwohl, P., Bayer, P. and Blum, P., 2008. Cold plumes of ground source heat pumps: Their length and legal situation. Geophysical Research Abstracts 10. EGI2008-A-07946, Vienna: EGU General Assembly.

Haehnlein, S., Bayer, P, and Blum, P., 2010. International legal status of the use of shallow geothermal energy. Renewable and Sustainable Energy Reviews 14(9): 2611-2625.

Hamid, O., 2008. In-situ stress analysis of southwest Saskatchewan, M.Sc. Thesis, University of Saskatchewan.

Hamm, V. and Bazargan Sabet, B., 2010. Modelling of fluid flow and heat transfer to assess the geothermal potential of a flooded coal mine in Lorraine, France. Geothermics, 39(2): 177-186.

Hartley, R.P., 1978. Pollution Control Guidance for Geothermal Energy Development. Industrial Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio, EPA-600/7-78-101.

Hattemer, B. and Kavanaugh, S.P., 2005. Design temperature data for surface water heating and cooling systems. ASHRAE Transactions, 111(1): 695-701.

Hauksdottir, S., Enegren, E.G. and Russell, J.K., 1994. Recent basaltic volcanism in the Iskut-Unuk rivers area, northwestern British Columbia. In: Current research, Geological Survey of Canada, 1994-A, 57-67.

Hawkes, C.D. and Hamid, O., 2008. In-situ stress regime in the Viking Formation, southwest Saskatchewan, Proceedings of the 61st Canadian Geotechnical Conference, Edmonton, AB, September 21-24, Paper No. 418.

Health Canada, 2006. It's Your Health: Arsenic in Drinking Water. Catalogue # H50-3/6-2004E (Updated August 2006).

Heffer, K.J. and Lean, J.C., 1991. Earth stress orientation - a control on, and guide to flooding directionality in a majority of reservoirs. In: B. Linville (ed.), International Reservoir Characterization Technical Conference, Tulsa / Okla, vol. III, 800 - 822.

Hickson, C.J., 1987. Quaternary volcanics of the Wells Gray-Clearwater area, east-central British Columbia. Ph.D. thesis, University of British Columbia, Vancouver, British Columbia, 357 p.

Hickson, C.J., 2000. Physical controls and resulting morphological forms of Quaternary ice-contact volcanoes in western Canada. Geomorphology, 32, 239-261.

Hickson, C.J. and Souther, J.G., 1984. Late Cenozoic volcanic rocks of the Clearwater – Wells Gray area, British Columbia. Canadian Journal of Earth Sciences, 21, 267-277.

Hickson, C.J. and Edwards, B.E., 2001. Volcanoes and volcanic hazards. In: Brooks, G.R. (ed.), A Synthesis of Geological Hazards in Canada. Geological Survey of Canada, Bulletin, 548, 145-181.

Hidalgo, J.J., Carrera, J. and Dentz, M., 2009. Steady state heat transport in 3D heterogeneous porous media. Advances in Water Resources 32: 1206-1212.

Hitchon, B., 1968. Rock volume and pore volume data for plains region of Western Canada Sedimentary Basin between latitudes 49^o and 60^{o}N. Bull. Am. Ass. Petrol. Geol, 52, 2318-2323.

Hitchon, B., 1984. Geothermal gradients, hydrodynamics, and hydrocarbon occurrences, Alberta, Canada. American Association of Petroleum Geologists Bulletin, 68: 713-743.

Hitchon,B. and Friedman, I., 1969. Geochemistry and origin of formation waters in the Western Canada Sedimentar Basin - 1. stable isotopes of hydrogen and oxygen. Geochim. Cosmochim. Acta, 33, 1321-1349.

Hochstein, M.P., 1990. Classification and assessment of geothermal resources. In: Dickson MH, Fanelli M, editors. Small geothermal resources - A guide to development and utilisation. Rome Italy, UNITAR/UNDP Centre on Small Energy Resources: 31-59.

Hokanson, K.E.F., McCormick, J.H., Jones, B.R. and Tucker, J.H., 1973. Thermal requirements for maturation, spawning, and embryo survival of the brook trout, *Salvelinus fontinalis*. Journal of Fisheries Resources Board of Canada 30: 975–984.

Hoogwijk, M., 2004. Dissertation: On the global and regional potential of renewable energy sources. University Utrecht, The Hague, Netherlands.

Huenges, E., 2008 Geothermal power generation. Energy from the depths of the earth Renewable Energy ed R Wengenmayr and T Bhurke (New York: Wiley)

Hutchence, K., Vigrass, L.W., Law, A.G. and Weston. J.H., 1984. Modelling of the Regina geothermal aquifer. In - Energy Developments: New Forms, Renewables, Conservation, Ed.Curtis,F.A.,Proc.Energex Conf., 309-313.

Hyndman, R.D. and Lewis,T.J., 1999. Geophysical consequences of the Cordillera - Craton thermal transition in southwestern Canada. Tectonophysics, 306, 397-422.

IEA, 2010. World Energy Outlook 2010, Paris, France 731p.

IF Technology, 1995. Underground thermal energy storage: State of the art 1994. Arnhem, The Netherlands.

IGA (International Geothermal Association), 2004. http://www.geothermal-energy.org/314,what_is_geothermal_energy.html

Ingebritsen, S.E., Sherrod, D.R. and Mariner, R.H., 1996. Reply to comment by D.D. Blackwell and G.R. Priest on "Rates and patterns of groundwater flow in the Cascade Range volcanic arc, and the effect on subsurface temperatures": Journal of Geophysical Research 101:17,569-17, 576.

IPCC (Intergovernmental Panel on Climate Change), 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the

Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jenne, E.A., Andersson, O. and Willemsen, A., 1992. Well, hydrology, and geochemistry problems encountered in ATES systems and their solutions. In: Proceedings of the 1992 Intersociety Energy Conversion Engineering Conference, San Diego, California, August 3-4, 1992.

Jenne, E.A., Zipperer, J.P. and Vail, L.W., 1994. H2O TREAT: Applications to ATES sites. In: Proceedings of the Symposium on Aquifer Thermal Energy Storage, Tucaloosa, Alabama, November 14-15, 1994.

Jennejohn, D., 2010. US Geothermal Power Production and Development Update. Geothermal Energy Association, Washington, D.C.

Jennejohn, D., Blodgett, L. and Gawell, K., 2009. GEA Issue Brief: Geothermal Energy and Water Consumption. Geothermal Energy Association. Retrieved November, 2009. < http://www.geo-energy.org/publications/reports.asp>

Jessop, A.M., 1976. Geothermal Energy from Sedimentary Basins. Energy, Mines and Resources Canada, Earth Physics Branch, Geothermal Series Number 8. 9 p.

Jessop, A. M., 1990a. Terrestrial heat flow in Canada. In Slemmons, D.B., Engdahl, E.R., Zoback, M.D., and Blackwell, D.D., eds., Neotectonics of North America: Boulder, Colorado, Geological Society of America, Decade Map Volume 1.

Jessop, A.M., 1990b. Thermal Geophysics. Developments in Solid Earth Geophysics, 17, 306p.

Jessop, A.M., 2008a. Review of National Geothermal Energy Program: Phase 1 – Geothermal Potential of Sedimentary Basins. Geol. Survey Canada, Open File 5690.

Jessop, A.M., 2008b. Review of National Geothermal Energy Program, Phase 2 - Geothermal potential of the Cordillera. Geol.Surv.Canada, Open File 5906, 128pp.

Jessop, A.M., Lewis, T.J., Judge, A.S., Taylor, A.E. and Drury, M.J., 1984a. Terrestrial heat flow in Canada Tectonophysics, 103 (1-4). pp. 239-261.

Jessop, A.M., Souther, J.G., Lewis, T.J. and Judge, A.S., 1984b. Geothermal measurements in northern British Columbia and southern Yukon Territory. Can J Earth Sci 21, 599–608.

Jessop, A.M., Ghomeshei, M.M. and Drury. M., 1991. Geothermal energy in Canada. Geothermics 20 369-385.

Jessop, A.M., MacDonald, J.K. and Spence, H., 1995. Clean energy from abandoned mines at Springhill, Nova Scotia. Energy Sources. 17, p. 93-106.

Jessop, A.M, Allen, V.S., Bentkowski, W., Burgess, M., Drury, M., Judge, A.S., Lewis, T., Majorowicz, J., Mareschal, J.C. and Taylor, A.E., 2005. The Canadian geothermal data compilation Geological Survey of Canada, Open File 4887, one CD.

John M. Booth Engineering Ltd, 1985. Outline report on the minewater geothermal heat source, Unpublished report to Earth Physics Branch.

Jones, F.W. and Majorowicz, J.A., 1987. Regional trends in radiogenic heat generation in th Precambrian basement of the Western Canadian Basin: Geophys. Res. Lett., v. 14, no. 3, p. 268–271.

Kagel, A., Bates, D. and Gawell, K., 2007. A Guide to Geothermal Energy and the Environment. Geothermal Energy Association, Washington, D.C., pp.75.

Katherine Arkay Consulting, 1992. Geothermal energy from abandoned mines: a methodology for an inventory, and inventory data for abandoned mines in Quebec and Nova Scotia. Geol.Surv.Can., Open File 3825.

Klotzbücher, T., Kappler, A., Straub, K.L. and Haderlein, S.B., 2007. Biodegradability and groundwater pollutant potential of organic anti-freeze liquids used in borehole heat exchangers. Geothermics 36: 348-361.

Koch, M. and Ruck, W., 1992. Injection of CO_2 for the inhibition of scaling in ATES systems. In: Proceedings of the 1992 Intersociety Energy Conversion Engineering Conference, San Diego, California, August 3-4, 1992.

Koutinas, G., 1989. High salinity fluid handling in Milos geothermal field. Geothermics, Vol.18, No. 1/2, pp. 175-182.

Kristmannsdóttir, H. and Ármannsson, H., 2003. Environmental aspects of geothermal energy utilization. Geothermics, 32: 451-461.

Lachenbruch, A. H., 1970. Crustal temperatures and heat production: implications of the linear heat-flow relation: J. Geophys. Res., v. 75, no. 17, p. 3291–3300.

Lachenbruch, A. H., 1971. Vertical gradients of heat production in the continental crust. 1. Theoretical detectability from near-surface measurements: J. Geophys. Res., v. 76, no. 17, p. 3842–3860.

Lachenbruch, Arthur H., 1973. Differentiation and the Gravitational Driving Force for Material Rising at an Oceanic Ridge. Journal of Geophysical Research,Vol. 78, Issue 5, pp.825-831.

Lefebvre, R., Hockley, D., Smolensky, J. and Gelinas, P.J., 2001a. Multiphase transfer processes in waste rock piles producing acid mine drainage 1: Conceptual model and system characterization. Journal of Contaminant Hydrology, 52(1-4): 137-164.

Lefebvre, R., Hockley, D., Smolensky, J. and Lamontagne, A., 2001b. Multiphase transfer processes in waste rock piles producing acid mine drainage 2. Applications of numerical simulation. Journal of Contaminant Hydrology, 52(1-4): 165-186.

Leonard, E.M., 1995. A varve-based calibration of the Bridge River tephra fall. Canadian Journal of Earth Sciences, 32, 2098-2101.

Lewis,T.J., 1991. Heat flux in the Canadian Cordillera. In - Neotectonics of North America, Ed. Slemmons, Engdahl, Zoback, and Blackwell, Geol.Soc.Am., Decade Map Volume 1, 445-456.

Lewis, J.F. and Jessop, A.M., 1981. Heat flow in the Garibaldi Volcanic Belt, a possible Canadian geothermal resource area. Can.J.Earth Sci., 18, 366-375.

Lewis, T.J. and Bentkowski,W.H., 1988. Potassium, uranium, and thorium concentrations of crustal rocks: a data file. Geol.Surv.Can., Open File 1744, 9pp + tables

Lewis, T.J. and Souther, J.G., 1978. Meager Mountain, B.C. – a possible geothermal energy resource. Earth Physics Branch, Energy, Mines and Resources Canada, Geothermal Series No. 9.

Lewis, T.J., Allen, V.S., Taylor, A.E. and Jessop, A.M., 1979. Temperature observations during drilling of two 400 m wells in the Coryell intrusives north of Grand Forks, British Columbia. Earth Phys.Br., Open File 79-2,16pp+diagr

Lewis, T.J., Bennetts, H., Allen, V.S. and Chan, F., 1984. Uranium, thorium and Potassium concentrations and heat generated in samples of crustal rocks. Earth Physics Br., Open File 84-15, 163pp

Lewis, T.J., Bentkowski, W.H. and Hyndman, R.D., 1992. Crustal Temperatures near the lithoprobe southern Canadian Cordillera Transect. Canadian Journal of Earth Sciences, 29: 1197-1214.

Lewis, T.J., Hyndman, R.D. and Fluck, P., 2003. Heat flow, heat generation, and crustal temperature in the Northern Canadian Cordillera: thermal control of tectonics. J.Geophys.Res., 108, B6, 2316

Lopez, S., Hamm, V. Le Brun, M, Schaper, L., Boissier, F., Cotiche, C. and Giuglaris, E. 2010. 40 Years of Dogger aquifer management in Ile-de-France, Paris Basin, France. Geothermics 39: 339-356.

Lowson, R.T., 1982. Aqueous oxidation of pyrite by molecular oxygen. Chemical Reviews, 82(5): 461-497.

Lund, J. W., 2007. Characteristics, development and utilisation of geothermal resources. Geo-Heat Centre Quarterly Bulletin, v.20, no. 2, p. 1-9.

Lund, J., Sanner, B., Rybach, L., Curtis, R. and Hellstrom G., 2004. Geothermal (Ground-Source) Heat Pumps: A World Overview. GHC Bulletin, September 2004, 1-10.

Lund, J. W., Freeston, D.H. and Boyd, T.L., 2005. Direct application of geothermal energy: 2005 Worldwide review. Geothermics 34: 691-727.

Lunis, B. and Breckenridge, R., 1991. Environmental considerations. In: Lienau, P.J. and Lunis, B.C., eds., Geothermal Direct Use, Engineering and Design Guidebook, Geo-Heat Center, Klamath Falls, Oregon, pp.437-445.

Majer, E.L., Baria, R., Stark. M., Oates, S., Bommer, J., Smith, B. and Asanuma, H., 2007. Induced seismicity associated with Enhanced Geothermal Systems, Geothermics 36, 185-222.

Majorowicz, J. A., 1996. Anomalous heat flow regime in the western margin of the north american craton, canada. Journal of Geodynamics*, 21*(2), 123-140.

Majorowicz, J.A. and Jessop, A.M., 1981a. Present heat flow and a preliminary geothermal history of the Central Prairies Basin, Canada. Geothermics, 10, 81-93.

Majorowicz, J.A. and Jessop, A.M., 1981b. Regional heat flow patterns in the Western Canadian Sedimentary Basin. Tectonophysics, 74, 209-238.

Majorowicz, J.A. and Embry, A., 1998. Present heat flow and paleogeothermal regime in the Canadian Arctic margin - analysis of industrial thermal data and coalification gradients. In - Heat flow and structure of the lithosphere, Ed: Cermak,V., Tectonophysics, 291, 141-159.

Majorowicz, J.A. and Grasby, S.E., 2010a. Heat flow. Depth-temperature variations and stored thermal energy for enhanced geothermal systems in Canada, Journal of Geophysics and Engineering, vol. 7, p. 232-241.

Majorowicz, J.A. and Grasby, S.E., 2010b. High Potential Regions for Enhanced Geothermal Systems in Canada, Natural Resources Research, Vol. 19, No.3, p177-188.

Majorowicz, J.A., Jones, F.W., Lam, H-L., Linville, A. and Nguyen, C.D., 1985. Topography and the subsurface temperature regime in the Western Canadian Sedimentary Basin: Implications for low-enthalpy geothermal energy recovery. Geothermics*,* 14, 175-187.

Majorowicz , J.A., Jones, F.W., Lam, H.L., and Jessop, A.M., 1985. Terrestrial heat flow and geothermal gradients in relation to hydrodynamics in the Alberta Basin, Canada. J. Geodyn*.* 4 , pp. 265–283.

Majorowicz, J.A., Jones, F.W. and Jessop, A.M., 1988. Preliminary geothermics of the sedimentary basins in the Yukon and Northwest Territories (60-70N)-Estimates from petroleum bottom-hole temperature data. *CSPG Bull.*.36, 39-51.

Majorowicz, J.A., Jessop, A.M. and Judge, A.S., 1995. Geothermal field, in J. Dixon, ed., Geological atlas of the Beaufort-Mackenzie: Geological Survey of Canada Miscellaneous Report 59, p. 33-37.

Majorowicz, J.A., Jessop, A.M. and Judge, A.S., 1996. Geothermal regime. In - Geological atlas of the Beaufort Mackenzie area, Ed J.Dixon, Geol.Surv.Can. Report 59, 33-37.

Majorowicz, J.A., Garven, G., Jessop, A.M. and Jessop, C., 1999. Present heat flow along a profile across the Western Canada Sedimentary Basin: the extent of hydrodynamic influence. In - Geothermics in basin analysis, Ed. Forster,A and Merriam,D.F. Kluwer/Plenum, 61-79.

Majorowicz, J., Jessop, A., Lane, M. and Larry S., 2005. “Regional Heat Flow Pattern and Lithospheric Geotherms in Northeastern British Columbia and Adjacent Northwest Territories, Canada”. Bulletin of Canadian Petroleum Geology. 53(1):51-66.

Majorowicz, J. A., Skinner, W., Safanda, J. and Gosnold, W., 2006. Differences between repeated borehole temperature logs in the southern Canadian Prairies- validating borehole climatology: Climate of the Past Discussion, v. 2, p. 1075–1104.

Majorowicz, J., Grasby, S.E. and Skinner, W., 2009. Estimation of shallow geothermal energy resources in Canada – Heat gain and sink. Natural Resources Research. Volume 18, Issue 2, Pages 95-108.

Malolepszy, Z., Demollin-Schneiders, E. and Bowers, D., 2005. Potential use of geothermal mine water in Europe. Proceedings of the World Geothermal Energy Congress, Antalya, 3 pp.

Markle, J.M. and Schincariol, R.A., 2007. Thermal plume transport from sand and gravel pits – Potential thermal impacts. Journal of Hydrology 338: 174-195.

Marten, P.S., 1992. Effect of temperature variation on the incubation and development of Brook Trout eggs. The Progressive Fish-Culturist 54: 1–6.

Mathews, W.H., 1989. Neogene Chilcotin basalts in south-central British Columbia: geology, ages, and geomorphic history. Canadian Journal of Earth Sciences, 26, 969-982.

McLellan, P.J., 1988. In Situ Stress Prediction and Measurement by Hydraulic Fracturing, Wapiti, Alberta. Journal of Canadian Petroleum Technology, v. 27, no. 2, pp. 85-95.

McCray, K.B., 1997. Guidelines for the construction of vertical boreholes for closed loop heat pump systems. National Ground Water Association.

Michel, F.A. and Allen, D.M., 1997. Optimizing Well Configurations for Aquifer Thermal Energy Storage Systems. Paper in Proceedings of Megastock '97, 7th International Conference on Thermal Energy Storage, Sapporo, Japan, June 1997.

Miller, T.P. and Richter, D.H., 1991. Quaternary volcanism of the Alaska Peninsula and Wrangell Mountains, Alaska. In: Plafker, G., and Berg, H.C. (eds.), The Cordilleran Orogeny: Alaska, Boulder, Colorado, Geological Society of America, Geology of North America, G-1, 759-779.

MIT (Massachusetts Institute of Technology), 2006. The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century, pp. 372.

Monger, J.W.H., Price, R.A. and Templeman-Kluit, D.J., 1982. Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera. Geology, 10: 70-75.

Mossop, G.D. and Shetsen, I. (Editors), 1994. Geological Atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists and Alberta Research Council, 510 p.

Muffler, L.J.P., 1976. Tectonic and hydrologic control of the nature and distribution of geothermal resources. *In* Proceedings of Second United Nations Symposium on the Development and use of Geothermal Resources.

Muffler, P. and Cataldi, R., 1978. Methods for regional assessment of geothermal resources. Geothermics, 7, 53-89.

Nicholson, C. and Wesson, R.L., 1992. Triggered Earthquakes and Deep Well Activities. Pure and Applied Geophysics 139: 561-578.

Nurkowski, J.R., 1984. Coal quality, coal rank variation and its relation to reconstructed overburden, Upper Cretaceous and Tertiary plains coals, Alberta, Canada. American Association of Petroleum, Geologists Bulletin, v. 68, p. 285-295.

OEE 2009 http://oee.nrcan.gc.ca/publications/infosource/pub/home/Heating_and_Cooling_with_a_Heat Pump_Section4.cfm

Palmer, C.D. and Cherry, J.A., 1984. Geochemical reactions associated with low-temperature thermal energy storage in aquifers. Canadian Geotechnical Journal 21: 475-488.

Parks Canada, 2009. Species At Risk: Banff Springs Snail. Last modified April 15th, 2009. http://www.pc.gc.ca/nature/eep-sar/itm3/eep-sar3a.aspx

Parrish, R.R., Carr, S.D. and Parkinson, D.L., 1988. Eocene extensional tectonics and geochronology of the southern Omineca belt, British Columbia and Washington. Tectonics, 7: 181-212.

Pearl, R., 1976. Hydrological problems associated with developing geothermal energy systems. Groundwater, 14: 128-137.

PIC (Petroleum Information Corporation), 1979. The Geothermal Resource: Earth's Natural Heat Providing Energy Now. Petroleum Information Corporation, Denver, Colorado, pp.198.

Perlinger, J.A., Almendinger, J.E., Urban, N.R. and Eisenreich, S.J., 1987. Groundwater geochemistry of aquifer thermal energy storage; long-term cycle. Water Resources Research 23: 2215-2226.

Pollack, H.N., Hurter, S.J. and Johnson, J.R., 1993. Heat flow from the Earth's interior: Analysis of the global data set. Reviews of Geophysics, 31(3), 267±80.

Power, G., Brown, R. and Imhof, J., 1999. Groundwater and fish: Insights from northern North America. Hydrological Processes, 13: 401-422.

Pruess, K., 2006. Enhanced geothermal systems (EGS) using CO_2 as a working fluid – A novle approach for generating renewable energy with simultaneous sequestration of carbon, Geothermics 45: 351-367.

Rafferty, K., 2001. Design aspects of commercial open-loop heat pump systems. GHC Bulletin, March 2001, www.geoheat.oit.edu.

Rafferty, K., 2003. Ground water issues in geothermal heat pump systems. Ground Water, 41(4): 408-410.

Ramachandra, T. and Shruthi, B., 2007. Spatial mapping of renewable energy potential. Renewable and Sustainable Energy Reviews, 11: 1460-1480.

Raymond, J., 2010. Geothermal system optimization in mining environments, Ph.D. Thesis, Laval University, Québec, 223 pp.

Raymond, J. and Therrien, R., 2008. Low-temperature geothermal potential of the flooded Gaspé Mines, Québec, Canada. Geothermics, 37: 189-210.

Raymond, J., Therrien, R. and Hassani, F., 2008. Overview of geothermal energy resources in Québec (Canada) mining environments. In: N. Rapantova and Z. Hrkal (Editors), 10th International Mine Water Association Congress: Mine Water and the Environment. Technical university of Ostrava, Ostrava, 12 pp.

Raymond, J., Robert, G., Therrien, R. and Gosselin, L., 2010a. A novel thermal response test using heating cables. Proceedings of the World Geothermal Congress, Bali, 8 pp.

Raymond, J., Therrien, R. and Gosselin, L., 2010b. Low-temperature geothermal energy in mining environments. CIM Journal, 1(2): 140-149.

Raymond, J., Therrien, R., Gosselin, L. and Lefebvre, R., 2011. Numerical analysis of thermal response tests with a groundwater flow and heat transfer model. Renewable Energy, 36(1): 315-324.

Raymond, J., Therrien, R., Gosselin, L. and Lefebvre, R., In Press. A review of thermal response test analysis using pumping test concepts. Ground Water, doi:10.1111/j.1745-6584.2010.00791x.

Reed, M.J. and Campbell, G.E., 1975. "Environmental Impact of Development in the Geysers Geothermal Field, USA.", Proceedings from the Second United Nations Symposium on the Development and Use of Geothermal Resources, May 20-29, 1975, San Francisco, pp. 1399-1410.

Reiter, M., and Tovar, R.J.C., 1982. Estimates of terrestrial heat flow in northern Chihuahua, Mexico, based upon petroleum bottom hole temperatures, Geological Society of American Bulletin, 93, 613-624.

Reiter, M.A. and Jessop, A.M., 1985. Estimates of terrestrial heat flow in offshore eastern Canada. Can.J.Earth Sci., 22, 1503-1517.

Renz, A., Rühaak, W., Schätzl, P. and Diersch, H.-J.G., 2009. Numerical modeling of geothermal used of mine water: challenges and examples. Mine Water and the Environment, 28(1): 2-14.

Ritchie, A.I.M., 1994. Sulfide oxidation mechanisms: Controls and rates of oxygen transport. In: D.W. Blowes, and Jambor, J.L. (Editors), Short course handbook on environmental geochemistry of sulfide mine-wastes. Mineralogical Association of Canada, Waterloo, pp. 201-246.

Rodríguez, R. and Díaz, M.B., 2009. Analysis of the utilization of mine galleries as geothermal heat exchangers by means a semi-empirical prediction method. Renewable Energy, 34(7): 1716-1725.

Rohr, K.M.M., Govers, R., and Furlong, K.P., 1996. A new plate boundary model for the Pacific – North America – Juan de Fuca triple junction. Slave-NORthern Cordilleran Lithospheric Evolution (SNORCLE) and Cordilleran Tectonics Workshop, Lithoprobe Report, 50, 213-214.

Rothbaum, H.P. and Anderton, B.H., 1975. Removal of Silica and Arsenic from Geothermal Discharge Waters by Precipitation of Useful Calcium Silicates. Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, May 20-29, 1975, San Francisco, pp.1417-1425.

Roy, R.F., Blackwell, D.D. and Decker, E.R., 1972. “Continental heat flow.” In The Nature of the Solid Earth. Ed. E.C. Robertson, McGraw-Hill, New York, pp. 506-543.

Roy, R.F., Beck, A.E. and Touloukian, Y. S., 1981. Physical properties of rocks and minerals, in McGraw-Hill/CINDAS Data Series on Material Properties, vol. II-2, edited by Y. S. Touloukian and C. Y. Ho, pp. 408–481, McGraw-Hill, New York.

Rozanski, K., Araguas-Araguas, L. and Gonfiantini, R., 1993. Isotopic patterns in modern global precipitation, *in* Swart, P. K., Lohmann, K. C., McKenzie, J., and Savin, S., eds., Continental Isotope Indicators of Climate: Washington, American Geophysical Union Monograph 78, p. 1-36.

Rybach, L., 2003. Geothermal energy: Sustainability and the environment. Geothermics, 32: 463-470.

Santi, P.M., McCray, J.E. and Martens, J.L., 2006. Investigating cross-contamination of aquifers. Hydrogeology Journal 14: 51-68.

Saskatchewan Environment and Public Safety, 1989. Abandoned Mines Remedial Action Program 1989 Annual Report, Mines Pollution Control Branch.

Saskatchewan Environment and Resource Management, 2001. An Assessment of Abandoned Mines in Northern Saskatchewan (March 2001)

Saskatchewan Environment, 2002. An Assessment of Abandoned Mines in Northern Saskatchewan (Year 2), File R3160, (May 2002).

Saskatchewan Environment, 2003. An Assessment of Abandoned Mines in Northern Saskatchewan (Year 3), File R3278, (May 2003).

Shibacki, M. and Beck, F., 2003. Geothermal Energy for Electric Power: A REPP Issue Brief. Renewable Energy Policy Project, Washington, D.C.

Sigma H Consultants Ltd., 2002. In situ stress regime in the coal-bearing strata of the Northeastern Plains area of British Columbia – A study to identify areas of coal bed methane prospectivity. Contract Report for British Columbia Ministry of Energy and Mines. 182 p.

Sophocleous, M., 2002. Interactions between groundwater and surface water: The state of the science. Hydrogeology Journal, 10: 52-67.

Skouby, A. (ed.), 2008. Closed-Loop/Geothermal Heat Pump Systems. International Ground Source Heat Pump Association, Stillwater, OK.

Skulski, T., Francis, D. and Ludden, J., 1991. Arc-transform magmatism in the Wrangell volcanic belt. Geology, 19, 11-14.

Smith, S. L., 1998. Mapping the response of permafrost in Canada to climate warming In: Current Research - Geological Survey of Canada pp. 163-171

Souther, J.G., 1975. Geothermal potential of western Canada. Proc. U.N. Symp.Geothermal Res., San Francisco, 259-267.

Souther, J.G., 1977. Volcanism and tectonic environments in the Canadian Cordillera – a second look. In: Baragar, W.R.A., Coleman, L.C., and Hall, J.M. (eds.), Volcanic Regimes in Canada, Geological Association of Canada, Special Paper, 16, 3-24.

Souther, J.G., 1991. Volcanic Regimes, Chapter 14. In: Gabrielse, H., and Yorath, C.J. (eds.), Geology of the Cordilleran Orogen in Canada, Geological Survey of Canada, Geology of Canada, No. 4, 457-490.

Souther, J.G., Clague, J.J. and Mathewes, R.W., 1987. Nazko cone: Quaternary volcano in the eastern Anahim Belt. Canadian Journal of Earth Sciences, 24, 2477-2485.

Souther, J.G. and Yorath, C.J., 1991. Neogene Assemblages, Chapter 10. In: Gabrielse, H., and Yorath, C.J. (eds.), Geology of the Cordilleran Orogen in Canada, Geological Survey of Canada, Geology of Canada, No. 4, 373-401.

Sproule Associates Ltd., 1976. Report on study of geothermal resources in western Canadian sedimentary basins from existing data, phase one. Earth Phys. Br., Open File 77-13, 110pp+diagr.

Sproule Associates Ltd., 1978. Report on the acquisition of data on the lithological character of the sedimentary rocks, Western Canada. Unpublished report to Earth Physics Branch.

Sproule and Angus Ltd., 1981. Report on preliminary assessment of the potential applications of geothermal energy. Earth Physics Branch, EMR. Open File 81-7, 86 p.

Stasiuk, M.V., Hickson, C.J. and Mulder, T., 2003. The vulnerability of Canada to volcanic hazards. Natural Hazards, 28, 563-589.

Tester, J. W., Anderson, B.J., Batchelor, A.S., Blackwell, D.D., DiPippo, R., Drake, E.M., Garnish, J., Livesay, B., Moore, M.C., Nichols, K., Petty, S., Toksöz, M.N., Shrock, R.R. and Veatch, R.W., 2006. The future of geothermal energy, the impact of Enhanced Geothermal Systems on the United States in the 21st century: MIT Press, Cambridge, MA.

Therrien, R., McLaren, R.G., Sudicky, E.A. and Panday, S.M., 2010. HydroGeoSphere. A three-dimensional numerical model describing fully-integrated subsurface and surface flow and solute transport. Laval University, Québec, University of Waterloo, Ontario, 366 pp.

Thompson, A., 2010. Geothermal Development in Canada: Country Update. Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25-29 April, 2010.

Thorhallsón, S., Ragnars, K., Arnorsson, S. and Kristmannsdóttir, H., 1975. Rapid Scaling of Silica in Two District Heating Systems. Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, May 20-29, 1975, San Francisco, pp. 1445-1449.

Tomiya, A., 2000. Depth of magma chamber determined by experimental petrologic methods. Proc. World Geoth. Congress 2000, International Geothermal Association, 5 pages, on CD Rom 2000. (670 papers).

Tóth, A. and Bobok, E., 2007. A prospect geothermal potential of an abandoned copper mine. Proceedings of the Thirty-Second Workshop on Geothermal Reservoir Engineering, Stanford University, 3 pp.

Udd, J.E., 2000. A century of achievement - The development of Canada's minerals industries. CIM Special Volume, 52. Canadian Institute of Mining, Montréal, 206 pp.

US EPA (United States Environmental Protection Agency), 1973. Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety. Office of Noise Abatement and Control, Washington D.C., EPA-550/9-73-002.

US EPA (United States Environmental Protection Agency), 1977. Western Energy Resources and the Environment: Geothermal Energy. Office of Research and Development, Office of Energy, Minerals and Industry, Washington, D.C., EPA-600/9-77-010.

Valdez, V., Schorr, M., Quintero, M., Carillo, M., Zlatev, R., Stoytcheva, M. and Ocampo, J.D., 2009. Corrosion and scaling at Cerro Prieto geothermal field. Anti-Corrosion Methods and Materials, Vol. 56, No. 1, pp. 28-34.

Van Loon, L.J.M. and van der Heide, K., 1992. High–temperature ATES at the State University of Utrecht, The Netherlands. In Proceedings of the Intersociety Energy Conversion Engineering Conference, San Diego, California, August, 1992.

Vigrass, L.W., 1979. Final well report, U or R Regina 3-8-17-19 (W.2nd.Mer.) Saskatchewan. Earth Physics Branch Open File 79-9, 36pp+diagrams.

Vigrass, L.W., 1980. Completion and pump test, U. of Regina 3-8-17-19, phase 1b - geothermal project. Earth Phys.Br., Open File 80-6, 90pp.

Vigrass, L.W., Kent, D.M. and Leibel, R.J., 1978. Low-grade geothermal project, geological feasibility study, Regina - Moose Jaw area, Saskatchewan. Earth Physics Branch Open File 78-4, 79pp + append.

Watzlaf, G.R. and Ackman, T.E., 2006. Underground mine water for heating and cooling using geothermal heat pump systems. Mine Water and the Environment, 25(1): 1-14.

White, D.E., 1973. Characteristics of geothermal resources. In: Kruger, P. and Otte, C.,eds., Geothermal Energy, Stanford University Press, Stanford, pp. 69-94.

White, P.J., Lawless, J.V., Terzaghi, S. and Okada, W., 2005. "Advances in Subsidence Modelling of Exploited Geothermal Fields." Proceedings of the World Geothermal Congress, Antalya, Turkey, 24-29, April 2005.

Wieber, G. and Pohl, S., 2008. Mine water: a source of geothermal energy - examples from the Rhenish Massif. In: N. Rapantova and Z. Hrkal (Editors), 10th International Mine Water Association Congress: Mine Water and the Environment. Technical university of Ostrava, Ostrava, pp. 4.

WEC (World Energy Council) 2007. 2007 Survey of Energy Resources: Geothermal Energy.

WHO (World Health Organization) 2000. Air Quality Guidelines, 2nd Edition. WHO Regional Office for Europe, Copenhagen, Denmark.

Woodland, D. C. and Bell, J. S., 1989. In situ stress magnitudes from mini-frac records in Western Canada, Journal of Canadian Petroleum Technology, Vol. 28, Issue 5, pp. 22-31.

Younger, P.L., 2008. Ground-coupled Heating-Cooling Systems in Urban Areas: How Sustainable Are They? Bulletin of Science, Technology and Society 28:174-182.

Zhou, S., 1997. A method of estimating horizontal principal stress magnitudes from stress-induced wellbore breakout and leak-off tests and its application to petroleum engineering, Petroleum Geoscience, Vol. 3, Issue 1, pp. 57-64.

Zhu, K., Blum, P., Ferguson, G., Balke, K.-D. and Bayer, P., 2010. Geothermal potential of urban heat islands. Environmental Research Letters 5: 04402 (6 pp).

Zoback, M.L. and Zoback, M., 1980. State of stress in the conterminous United States, Journal of Geophysical Research, Vol. 85, Issue B11, pp. 6113-6156.

Zoback, M.D., Moos, D., Mastin, L. and Anderson, R. N., 1985. Wellbore breakouts and in-situ stress. Journal of Geophysical Research, v. 90, p. 5523-5530.

APPENDIX 1

1. CANADIAN GEOTHERMICS BIBLIOGRAPHY

Adams,J. 1993. A suite of type temperature-depth profiles in permafrost for areas of Holocene shoreline regression and marine transgression, Arctic Canada. Geol.Surv.Can. Open File 2656

Allen, D.M. 1988. The Permafrost Regime in the Mackenzie Delta-Beaufort Sea Region, N.W.T. and its Paleoclimatic Implications. M.Sc. Thesis, Department of Earth Sciences, Carleton University, Ottawa, Ontario, 154 pp.

Allen, D., Michel, F. and Judge, A. 1988. The permafrost regime in the Mackenzie Delta-Beaufort Sea Region, N.W.T. and its significance to the reconstruction of the paleoclimatic history. Journal of Quaternary Science, 3(1): 3-13..

Allen D., Michel, F. and Judge, A. 1988. Paleoclimate and permafrost in the Mackenzie Delta. In: Proceedings of the Fifth International Conference on Permafrost, Trondheim, Norway.

Allis,R.G. 1975. Geothermal measurements in five small lakes of northwestern Ontario, Canada. Thesis, M.Sc., University of Toronto.

Allis,R.G. 1979. A heat production model for stable continental crust. Tectonophysics, 57, 151-165

Allis,R.G. and Garland,G.D. 1976. Geothermal measurements in five small lakes of northwest Ontario. Can.J.Earth Sci., 13, 987-992

Allis,R.G. and Garland,G.D. 1979. Heat flow measurements under some lakes in the Superior Province of the Canadian Shield. Can.J.Earth Sci., 16, 1951-1964

Allis,R.G. and Garland,G.D. 1980. Heat flow measurements under some lakes in the Superior Province of the Canadian Shield - reply. Can.J.Earth Sci., 17,-1108-1110

Anderssen,R.S. and Saull,V.A. 1973. Surface temperature history determinations from borehole measurements. Math.Geol., 5, 269-283

Anglin,F.M. 1964. Subsurface temperature in Western Canada. Thesis, M.Sc., Univ.Western Ontario

Anglin,F.M. and Beck,A.E. 1964. The use of terrestrial heat flow data in interpreting regional geology. Proc.Third Ann.Conf.Ont.Pet.Inst., 14pp

Anglin,F.M. and Beck,A.E. 1965. Regional heat flow patterns in western Canada. Can.J.Earth Sci., 2, 176-182

Arctic geotechnical group. 1982. Acquisition of geothermal data in offshore wells - phase 1. Earth Physics Br., Open File 82-14, 142pp

Ashwal,L.D., Morgan,P., Kelley,S.A. and Percival,J.A. 1987. Heat production in an Archaean crustal profile and impklications for heat flow and mobilisation of heat-producing elements. Earth,Planet.Sci.Lett., 85, 439-450

Bachu,S. 1985. Influence of lithology and fluid flow on the temperature distribution in a sedimentary basin: a case study from the Cold Lake area, Alberta, Canada. Tectonophysics, 120, 257-284

Bachu,S. 1987. Convective versus conductive heat flow in the central Alberta part of the Western Canada Sedimentary Basin. Rev.Bras.Geofis., 5, 127-190

Bachu,S. 1988. Analysis of heat transfer processes and geothermal pattern in the Alberta Basin, Canada. J.Geophys.Res.,93, 7767-7781

Bachu,S. 1993. Basement heat flow in the Western Canada Sedimentary Basin. Tectonophysics, 222, 119-133

Bachu,S. and Burwash,R.A. 1991. Regional-scale analysis of the geothermal regime in the Western Canada Sedimentary Basin. Geothermics, 20, 387-407

Beach,R.D.W., Jones,F.W. and Majorowicz,J.A. 1987. Heat flow and heat generation estimates for the Churchill basement of the Western Canadian Basin in Alberta, Canada. Geothermics, 16, 1-16

Beck,A.E. 1962. Terrestrial flow of heat near Flin Flon, Manitoba. Nature, 195, 368-369

Beck,A.E. 1963. Lightweight borehole temperature measuring equipment for resistance thermometers. J.Sci.Inst., 41, 452-454

Beck,A.E. 1964. Flusso di calore terrestre ed energia geotermica. La Scuola in Azione San Donato Milanese, Ente Nazionale Idrocarburi, E.N.I., 165-189

Beck,A.E. 1965. Techniques of measuring heat flow on land. In - Terrestrial Heat Flow, Ed.Lee, Am.Geophys.Un.Monograph 8, 24-57

Beck,A.E. 1966. Problems in measuring temperature and terrestrial heat flow in deep boreholes. In - Drilling for scientific purposes, Ed.Findlay & Smith, Geol.Survey Can. Paper 66-13, 77-84

Beck,A.E. 1967. Heat flow studies. Geol.Surv.Can., Paper 67-41, 133-146

Beck,A.E. 1970. Non-equivalence of oceanic and continental heat flows and other geothermal problems. Comments Earth Sci.Geophys., 1, 29-34

Beck,A.E. 1971. Prospects for geothermal power. Comments Earth Sci.Geophys., 1, 139-149

Beck,A.E. 1976. An improved method of computing the thermal conductivity of fluid-filled sedimentary rocks. Geophysics, 41, 133-144

Beck,A.E. 1976. The use of thermal resistivity logs in stratigraphic correlation. Geophysics, 41, 300-309

Beck,A.E. 1977. A potential systematic error when measuring the thermal conductivity of porous rocks saturated with a low-conductivity fluid. Tectonophysics, 41, 9-16

Beck,A.E. 1977. Climatically perturbed temperature gradients and their effect on regional and continental heat-flow means. Tectonophysics, 41, 17-39

Beck,A.E. 1980. Heat flow measurements under some lakes in the Superior Province of the Canadian Shield - discussion. Can.J.Earth Sci., 17,-1108-1110

Beck,A.E. 1982. Precision logging of temperature gradients and the extraction of past climate. Tectonophysics, 83, 1-11

Beck,A.E. 1987. The maturaion of geothermics as a discipline and some unresolved problems. Rev.Bras.Geofis., 5, 73-90

Beck,A.E. 1988. Thermal properties: methods for determining thermal conductivity and thermal diffusivity. In - Handbook of terrestrial heat-flow density determination, Ed.Haenel,R., Rybach,L., Stegena,L., Kluwer Acas Publ., 87-124

Beck,A.E. 1992. Inferring past climatic change from subsurface temperature profiles: problems and methods. Palaeogeog.Palaeoclim.Palaeoecol., 98, 73-80

Beck,A.E. and Balling,N. 1988. Determination of virgin rock temperatures. In - Handbook of terrestrial heat-flow density determination, Ed.Haenel,R., Rybach,L., Stegena,L., Kluwer Acas Publ., 59-85

Beck,A.E. and Beck,J.M. 1958. On the measurement of the thermal conductivities of rocks by observations on a divided bar apparatus. Trans.Am.Geophys.Un., 39, 1111-1123

Beck,A.E. and Judge,A.S. 1969. Analysis of heat flow data-detailed observations in a single borehole. Geophys.J.R.Astr.Soc., 18, 145-158

Beck,A.E. and Logis,Z. 1963. Terrestrial flow of heat in the Brent Crater. Nature, 201, 383

Beck,A.E. and Mustonen,E. 1972. Preliminary heat flow data from Ghana. Nature,Phys.Sci., 235, 172-174

Beck,A.E. and Neophytou,J.P. 1968. Heat flow and underground water flow in the Coronation Mine area. In - Symposium on the Geology of Coronation Mine, Saskatchewan, Ed.Byers, Geol.Surv.Can.Paper 68-5, 229-239

Beck,A.E. and Sass,J.H. 1966. A preliminary value of heat flow in the Muskox Intrusion near Coppermine, N.W.T., Canada. Earth,Planet.Sci.Lett., 1, 123-129

Beck,A.E. and Shen,P.Y. 1985. Temperature distribution in flowing liquid wells. Geophysics, 50, 1113-1118

Beck,A.E. and Shen,P.Y. 1989. On a more rigorous approach to geothermic problems. Tectonophysics, 164, 83-92

Beck,A.E., Anglin,F.M., and Sass,J.H. 1971. Analysis of heat flow data - in situ thermal conductivity measurements. Can.J.Earth Sci., 8, 1-19

Beck,A.E., Hamza,V.M. and Chang,C.C. 1976. Analysis of heat flow data - correlation of thermal resistivity and shock metamorphic grade and its use as evidence for an impact origin of the Brent Crater. Can.J.Earth Sci.,13, 929-2936

Beck,A.E., Shen,P.Y., Beltrami,H., and others. 1992. A comparison of five different analyses in the interpretation of five borehole temperature data sets. Palaeogeog. Palaeoclim. Palaeoecol., 98, 101-112

Beck,A.E., Wang,K. and Shen,P.Y. 1985. Sub-bottom temperature perturbations due to temperature variations at the boundary of inhomogeneous lake or ocean sediments.. Tectonophysics, 121, 11-24

Beck,J.M. and Beck,A.E. 1965. Computing thermal conductivities of rocks from chips and conventional specimens. J.Geophys.Res., 70, 5227-5239

Becker,K., Langseth,M.G. and Hyndman,R.D. 1984. Temperature measurements in Hole 395a, Leg 78b. Init.Rept.Deep Sea Drilling Proj., 78. 689-698

Beltrami,H. 2001. Surface heat flux histories from geothermal data: inferences from inversion. Geophys.Res.Lett., 28, 655-658.

Beltrami,H. and Bourlon,E. 2004. Ground warming patterns in the northern hemisphere during the last five centuries. Earth,Planet.Sci.Lett., 227, 169-179

Beltrami,H. and Mareschal,J.C. 1992. Ground temperature histories for central and eastern Canada from geothermal measurements: little ice age signature. Geophys.Res.Lett., 19, 689-692

Beltrami,H. and Taylor,A.E. 1995. Records of climatic change in the Canadian Arctic: towards calibrating oxygen isotope data with geothermal data. Glob.,Planet.Change, 11, 127-138

Beltrami,H., Jessop,A.M. and Mareschal,J.C. 1992. Ground temperature histories in eastern and central Canada: evidence from geothermal measurements. Palaeogeog. Palaeoclim. Palaeoecol., 98, 167-184

Beltrami,H., Wang,J. and Bras,R.L. 2000. Energy balance at the Earth's surface: heat flux history in eastern Canada. Geophys.Res.Lett., 27, 3385-3388

Ben Dhia,H., Jones,F.W., Meddeb,N., and two others. 1992. Shallow geothermal studies in Tunisia: comparison with deep subsurface information. Geothermics, 21, 503-517

Bentkowski,W.H. and Lewis,T.J. 1983. Preliminary results of shallow drilling in the Garibaldi Volcanic Belt, British Columbia, 1982. Earth Physics Br., Open File 83-23, 38 pp

Bentkowski,W.H. and Lewis,T.J. 1984. Preliminary rsults from shallow drilling in the Alert Bay Volcanic Belt, 1982. Earth Physics Br., Open File 84-2, 16 pp

Bentkowski,W.H. and Lewis,T.J. 1985. Preliminary results from shalow drilling in the Anahim Volcanic Belt, B.C. Earth Physics Br., Open File 85-9 19 pp

Bentkowski,W.H. and Lewis,T.J. 1986. Heat flux in the Raft Batholith, central British Columbia. Geol.Surv.Can., Open File 1337, 24pp

Bentkowski,W.H. and Lewis,T.J. 1988. Thermal measurements in the Fraser Valley, British Columbia. Geol.Surv.Can., Open File 1743, 19pp

Bentkowski,W.H. and Lewis,T.J. 1989. Thermal measurements in Cordilleran boreholes of opportunity 1984-1987. Geol.Surv.Can., Open File 2048, 31pp

Bentkowski,W.H. and Lewis,T.J. 1994. Heat flow determinations in the Cordillera 1988-1992. Geol.Surv.Canada, Open File 2981, 34pp

Bodri,B. and Jessop,A.M. 1989. Geothermal model of the continental margins of eastern Canada. Tectonophysics, 164, 139-150

Bristow,Q. and Conaway,J.G. 1984. Temperature gradient measurements in boreholes using low noise high resolution digital techniques. Current Research, B, Geol.Surv.Can. Paper 84-1B, 101-108

Burgess,M.M. 1984. Summary of heat flow studies in the Sohm Abyssal Plain: C.S.S.Hudson cruise 80-016. Atomic Energy Can.Ltd., Tr-242

Burgess,M.M. 1986. A discussion of non-linear temperature profiles at six closely-spaced heat flow sites, southern Sohm Abyssal Plain, northwest Atlantic Ocean. Deep-sea Res., 33, 1213-1224

Burgess,M.M. and Judge,A.S. 1981. Heat flow studies in the Sohm Abyssal Plain and their relevance to nuclear waste disposal investigations. Earth Physics Br., Open File 81-15, 21pp and Appendices

Burgess,M.M. and Riseborough,D.W. 1989. Measurements frequency requirements for permafrost ground temperature monitoring: analysis of Norman Wells pipeline data, Northwest Territories and Alberta. Geol.Surv.Can., Paper 89-1D, 69-75

Burgess,M.M., Judge,A.S. and Taylor,A.E. 1982. Yukon ground temperature data collection - 1966-August 1981. Earth Physics Br., Open File 82-1, 138pp

Burgess.M.M. and Naufal,J.A. 1990. Norman Wells pipeline monitoring sites, ground temperature data file. Geol.Surv.Can., Open File 2155, 201pp

Burwash,R.A. 1979. Uranium and thorium in the Precambrian basement of western Canada. Can.J.Earth Sci., 16, 472-483

Butler,R.B. 1961. Terrestrial heat flow in the St. Lawrence Lowland of Quebec. Thesis, Ph.D., MGill Univ. 55pp

Caritat,P.de. 1993. Heat: a Fortran computer program for calculating 1-D conductive and advective heat transport in geological formations. Comput.Geosci., 19, 673-689

Caron, M-E, Grasby, S.E., and Ryan, M.C. (2008) Spring water trace element geochemistry: a tool for resource assessment and reconnaissance mineral exploration. Applied Geochemistry, 23, 3561-3578.

Cermak,V. 1971. Underground temperature and inferred climatic temperature of the past millenium. Palaeography, Palaeoclimatology, Palaeoecology. 10, 1-19

Cermak,V. and Jessop,A.M. 1971. Heat flow, heat generation, and crustal temperature in the Kapuskasing area of the Canadian Shield. Tectonophysics, 11, 287-303

Cermak,V. and Jessop,A.M. 1972. Heat flow and heat production in the Canadian Shield. Geothermics, 1, 70-72

Chen,Y. and Beck,A.E. 1991. Application of the boundary element method to a terrestrial heat flow problem. Geophys.J.Int., 107, 25-35

Conaway,J.G. 1976. Continuous logging of borehole temperature gradients. Thesis, Ph.D., Univ.Western Ontario

Conaway,J.G. 1977. Deconvolution of temperature gradient logs. Geophysics, 42, 823-837

Conaway,J.G. and Beck,A.E. 1977. Fine-scale correlation between temperature gradient logs and lithology. Geophysics, 42, 1401-1410

Conaway,J.G. and Beck,A.E>. 1977. Continuous logging of temperature gradients. Tectonophysics, 41, 1-7

Connolly,E.T. 1972. Geothermal Survey of North America progress report and associated data-gathering problems. Trans.Can.Well Logging Soc. Fourth Formn.Evaln.Symp.,37pp

Cook,F.A. 1983. The effect of lateral deformation on heat flow - heat production relations. Can.J.Earth Sci., 20, 1621-1630

Correia,A. and Jones,F.W. 1995. On the importance of measuring thermal conductivities for heat flow density estimates: an example from the Jeanne d'Arc Basin, offshore eastern Canada. Tectonophysics, 257, 71-80.

Correia,A., Jones,F.W. and Frocker,A. 1990. Terrestrial heat-flow density estimates for the Jeanne D'Arc Basin, offshore eastern Canada. Geophysics, 55, 1625-1633

Corriea,A. and Jones,F.W. 1991. The thermal regime of the Jeanne d'Arc Basin, offshore eastern Canada. Tectonophysics, 194, 357-361

Crain,I.K. 1969. A simple method of calculating climatic corrections to heat flow measurements. Can.J.Earth Sci., 6, 499-502

Crain,I.K. 1967. The influence of post-Wisconsin climatic change. Thesis, M.Sc., McGill Univ

Crain,I.K. 1968. The glacial effect and the significance of continental terrestrial heat flow measurements. Earth,Planet.Sci.Lett, 4, 69-72

Dallimore,S.R., Edwardson,K.A., Hunter,J.A. and two more. 1995. Composite geotechnical logs for two deep boreholes in the Fraser River Delta, British Columbia. Geol.Surv.Canada, Open File 3018.

Davis,E.E. and Lewis,T.J. 1984. Heat flow in a back-arc environment: Intermontane and Omineca Crystalline Belts, southern Canadian cordillera. Can.J.Earth Sci., 21, 715-726

Davis,E.E. and Villinger,H. 1992. Tectonics and thermal structure of the Middle Valley sedimented rift, northern Juan de Fuca Ridge.. Proc.Ocean Drill.Prog.Init.Rept., 139, 9-41

Davis,E.E., Chapman,D.S. Wang,K. and seven others. 1999. Regional heat flow variations across the sedimented Juan de Fuca Ridge eatern flank: constraints on lithospheric cooling and lateral hydrothermal heat transport. J.Geophys.Res., 104, 17675-17688.

Davis,E.E., Chapman,D.S., Forster,C.B. and Vilinger,H. 1989. Heat-flow variations correlated with buried basement topography on the Juan de Fuca Ridge flank. Nature, 342, 533-537

Davis,E.E., Chapman,D.S., Mottl,M.J., and others. 1992. FlankFlux: an experiment to study the nature of hydrothermal circulation in young ocean crust. Can.J.Earth Sci., 29, 925-952

Davis,E.E., Lister,C.R.B. and Sclater,J.G. 1984. Towards determining the thermal state of old ocean lithosphere: heat-flow measurements from the Blake-Bahama Outer Ridge, north-western Atlantic. Geophys.J.R.Astr.Soc., 78, 507-545

Davis,E.E., Lister,C.R.B., Wade,U.S. and Hyndman,R.D. 1980. Detailed heat flow measurements over the Juan de Fuca Ridge system. J.Geophys.Res., 85, 299-310

Doig,R. 1961. A further study of terrestrial heat flow in the St. Lawrence Lowlands of Quebec. Thesis,M.Sc.,Mcgill University, 73pp

Doig,R. and Saull,V.A. 1961. A new borehole thermometer. J.Geophys.Res., 66, 4263-4264

Drury,M.J. 1984. Assessment of the geothermal resources of Atlantic Canada. Proc. Intl. Symp. Energex 84, Regina, 285-290

Drury,M.J. 1984. On a possible source of error in extracting equilibrium formation temperature from borehole BHT data. Geothermics, 13, 175-180

Drury,M.J. 1984. Borehole temperature logging for the detection of water flow. Geoexploration, 22, 231-243

Drury,M.J. 1984. Perturbations to temperature gradients by water flow in crystalline rock formations. Tectonophysics, 103, 19-32

Drury,M.J. 1985. Heat flow and heat generation in the Churchill Province of the Canadian Shield, and their palaeotectonic significance. Tectonophysics, 115, 25-44

Drury,M.J. 1985. The Iceland Research Drilling Project crustal section: physical properties of some basalts from the Reydarfjordur borehole, Iceland. Can.J.Earth Sci., 22, 1588-1593

Drury,M.J. 1986. Heat flow in greenstone belts. Proc. Workshop on Tectonic evolution of greenstone belts, Houston, LPI Tech.Rept 86-10, 92-94

Drury,M.J. 1986. Thermal conductivity, thermal diffusivity, density and porosity of crystalline rocks. Earth Physics Br., Open File 86-5, 52pp

Drury,M.J. 1987. Thermal diffusivity of some crystalline rocks. Geothermics, 16, 105-115

Drury,M.J. 1987. Heat flow and heat generation in the Churchill Province of the Canadian Shield, and their paleotectonic significance: reply. Tectonophysics, 132, 347-349

Drury,M.J. 1987. Heat flow provinces reconsidered. Phys.Earth Planet.Inter., 49, 78-96

Drury,M.J. 1987. The thermal nature of the Canadian Appalachian crust. Tectonophysics, 133, 1-14

Drury,M.J. 1988. Tectonothermics of the North American Great Plains basement. Tectonophysics, 148, 299-307

Drury,M.J. 1988. A simple needle-probe method for measuring thermal diffusivity of unconsolidated materials. Geothermics, 17, 757-763

Drury,M.J. 1989. The heat flow - heat generation relationship: implications for the nature of the continental crust. Tectonophysics, 164, 93-106

Drury,M.J. 1989. Fluid flow in crystalline crust: detecting fractures by temperature logs. In - Hydrological regimes and their subsurface effects. Ed. Beck,A.E., Garven,G, Stegena,L. Am.Geophys.Un., Geophys.Momogr. 47, 129-135

Drury,M.J. 1991. Heat flow in the Canadian Shield and its relation to other geophysical parameters. In - Terrestrial heat flow and the lithosphere Structure, Ed. Cermak,V. and Rybach,L., Springer Verlag, 317-337

Drury,M.J. 1992. Tectonothermics of modern and ancient continental margins. In - Characterisation and comparison of ancient and mesozoic continental margins, Proc 8th Intl.Conf.Basement Tectonics, Ed.Bartholemew, Hyndman, Monk, Mason, Intl.Base. Tect.Assoc.Publ. 8, 27-36

Drury,M.J. and Jessop,A.M. 1982. The effect of a fluid-filled fracture on the temperature profile in a borehole. Geothermics, 11, 145-152

Drury,M.J. and Jessop,A.M. 1983. The estimation of rock thermal conductivity from mineral content - an assessment of techniques. Zbl.Geol.Palaont., 1, 35-48

Drury,M.J. and Lewis,T.J. 1979. Thermal studies in the Lac du Bonnet Batholith at Pinawa, Manitoba. Atomic Enrgy Can.Ltd, Tech.Rec. TR-12

Drury,M.J. and Lewis,T.J. 1983. Water movement within Lac du Bonnet Batholith as revealed by detailed thermal studies of three closely spaced boreholes. Tectonophysics, 95, 337-351

Drury,M.J. and Taylor,A.E. 1988. Some new measurements of heat flow in the Superior Province of the Canadian Shield. Can.J.Earth Sci., 24, 1486-1489

Drury,M.J., Allen,V.S. and Jessop,A.M. 1982. The measurement of thermal diffusivity of rock cores. Tectonophysics, 103, 321-333

Drury,M.J., Jessop,A.M. and Lewis, T.J. 1983. Geothermal logging for the detection of groundwater flow. Proc.Int.Conf.on Groundwater and Man, Sydney, 79-87

Drury,M.J., Jessop,A.M. and Lewis,T.J. 1984. The detection of groundwater flow by precise temperature measurements in boreholes. Geothermics, 13, 163-174

Drury,M.J., Jessop,A.M. and Lewis,T.J. 1987. The thermal nature of the Appalachians of eastern Canada. Tectonophysics, 133,1-14

Durham,W.B., Mirkovich,V.V. and Heard,H.C. 1987. Thermal diffusivity of igneous rocks at elevated pressure and temperature. J.Geophys.Res., 92, 11615-11634

Ferguson,G. and Beltrami,H. 2006. Transient lateral heat flow due to land-use changes. Earth,Planet.Sci.Lett., 242, 217-222.

Ferguson,G. and Woodbury,A.D. 2004. Subsurface heat flow in an urban environment. J.Geophys.Res. 109, B02402, doi:10,1029/2003JB002715.

Forster,C. and Smith,L. 1989. The influence of groundwater flow on thermal regimes in mountainous terrain: a model study. J.Geophys.Res., 94, 9439-9451

Fou,J.T.K. 1969. Thermal conductivity and heat flow at St. Jerome, Quebec. Thesis, M.Sc., McGill University, 79pp

Fountain,D.M., Furlong,K.P. and Salisbury,M.H. 1987. A heat production model of a shield area and its implications for heat flow - heat production relationship. Geophys.Res.Lett., 14, 283-286

Fountain,D.M., Salisbury,M.H. and Furlong,K.P. 1987. Heat production and thermal conductivity of rocks from the Pikwitonei Sachigo continental cross section, central Manitoba: implications for the thermal structure of the Archean crust. Can.J.Earth Sci., 24, 1583-1594

Furlong,K.P. and Chapman,D.S. 1987. Crustal heterogeneities and the thermal structure of the continental crust. Geophys.Res.Lett., 14, 314-317

Garland,G.D. and Lennox,D.H. 1962. Heat flow in western Canada. Geophys.J.R.Astr.Soc., 6, 245-262

Geo-engineering (M.S.T.) Ltd. 1990. Report of geothermal modelling, offshore temperature profiles at Angasak and Amauligak, Beaufort Shelf. Geol.Surv.Can., Open File 2226, 56pp

Geo-engineering (M.S.T.) Ltd. 1990. Modelling of offshore temperature profiles, final results for Amauligak and Angasak, Beaufort Shelf. Geol.Surv.Can., Open File 2227, 14pp

Geotech Ltd. 1984. Subsurface temperature data from wells north of sixty, Yukon - Northwest Territories. Earth Physics Br., Open File 84-28, 557 pp and 5 maps

Gosselin,C. and Mareschal,J.C. 2003. Variations in ground surface temperature histories in the Thompson Belt, Manitoba, Canada: environment and climate changes. Glob.Planet.Change, 39, 271-284

Gosselin,C. and Mareschal,J.C. 2003. Variations in ground surface temperature histories in the Thompson Belt, Manitoba, Canada: environmental and climate changes. Glob.,Planet.,Change, 39, 271-284

Gough,D.I. and Porath,H. 1970. Long-lived thermal structure under the southern Rocky Mountains. Nature, 226, 837-839

Gray,J.T. 1983. Extraction and compilation of available temperature and snow-fall in the Ungava Peninsula as input to geothermal modelling of quaternary palaeoclimates. Earth Physics Br., Open File 83-12, 38pp

Gretener,P.E. 1982. Geothermics: using temperature in hydrocarbon exploration. Am.Assn.Petr.Geol., Education Course Note Ser.17, 170pp

Guillou,L., Mareschal,J.C., Jaupart,C., and three others. 1994. Heat flow, gravity and structure of the Abitibi Belt, Superior Province, Canada: implications for mantle heat flow. Earth,Planet.Sci.Lett., 122, 103-123

Guillou-Frottier,L., Jaupart,C., Marescal,J.C. and four othe. 1996. High heat flow in the trans-Hudaon Orogen, central Canadian Shield. Geophys.Res.Lett., 23, 3027-3030.

Guillou-Frottier,L., Mareschal,J.C. and Musset,J. 1998. Ground surface temperature history in central Canada inferred from 10 selected borehole temperature profiles. J.Geophys.Res., 103, 7385-7397.

Guillou-Frottier,L., Mareschal,J.C., Jaupart,C. and three ot. 1995. Heat flow variations in the Grenville Province, Canada. Earth,Planet.Sci.Lett., 136, 447-460

Hackbarth,D.A. 1978. Groundwater temperatures in the Athabaska oil sands area, Alberta. Can.J.EArth Sci.,15, 1689-1700

Hamdani,Y. and Mareschal,J.C. 1993. Paleo heat flow of eastern Canada's passive margins. Tectoinophysics, 225, 107-121

Hamdani,Y., Mareschal,J.C. and Arkani-Hamed,J. 1994. Phase change and thermal subsidence of the Williston Basin. Geophys.J.Int., 116, 585-597

Hamza,V.M. 1973. Vertical distribution of radioactive heat production in the Grenville. Thesis, Ph.D., Univ.Western Ontario

Hamza,V.M. and Beck,A.E. 1972. Terrestrial heat flow, the neutrino problem, and a possible energy source in the core. Nature, 240, 343-344

Hamza,V.M. and Beck,A.E. 1975. Analysis of heat flow data - vertical variations of heat flow and heat producing elements in sediments. Can.J.Earth Sci., 12, 996-1005

Hart,S.R., Steinhart,J.S. and Smith,T.J. 1993. Terrestrial heat flow in Lake Superior. Can.J.Earth Sci., 31, 698-708

Hitchon,B. 1984. Geothermal gradients, hydrodynamics, and hydrocarbon occurrences, Alberta, Canada. Bull.Am.Ass.Petrol.Geol., 68, 713-743

Hobson,G.D., Beck,A.E. and Findlay,D.C. 1966. Notes on geophysical logs and borehole temperature measurement from the Muskox drilling project. In - Drilling for scientific purposes, Ed.Findlay & Smith, Geol.Survey Can. Paper 66-13, 108-122

Hyndman,R.D. 1976. Heat flow measurements in the inlets of southwestern British Columbia. J.Geophys.Res., 81, 337-349

Hyndman,R.D. and Drury,M.J. 1976. The physical properties of oceanic basement rocks from deep drilling on the mid-Atlantic Ridge. J.Geophys.Res., 81, 4042-4052

Hyndman,R.D. and Jessop,A.M. 1971. The Mid-Atlantic Rifdge near 45 degrees north, XV Thermal conductivity of dredge and drill core samples. Can.J.Earth Sci.,8, 391-393

Hyndman,R.D. and Lewis,T.J. 1995. Review: the thermal regime along the southern Canadian Cordillera lithoprobe corridor. Can.J.Earth Sci., 32, 1611-1617

Hyndman,R.D. and Lewis,T.J. 1999. Geophysical consequences of the Cordillera - Craton thermal transition in southwestern Canada. Tectonophysics, 306, 397-422

Hyndman,R.D. and Lewis,T.J. 1999. Geophysical consequences of the Cordillera-Craton thermal transition in southwestern Canada. Tectonophysics, 306, 397-422

Hyndman,R.D. and Rankin,D.S. 1972. The Mid-Atlantic Ridge near 45N. XVIII. Heat flow measurements. Can.J.Earth.Sci.,8,664-670

Hyndman,R.D., Christensen,N.I. and Drury,M.J. 1979. Seismic velocities, densities, electrical resistivities, porosities and thermal conductivities of core samples from boreholes into the islands of Bermuda and the Azores. In - Deep Drilling Results in the Atlantic Ocean, Ed.Talwani, Harrison & Hayes, Am.Geophys.Un. Maurice Ewing Ser. 2, 94-112

Hyndman,R.D., Christensen,N.I. and Drury,M.J. 1984. The physical properties of basalt core samples from deep sea drilling project Leg 78b Hole 395a. Init.Rept.Deep Sea Drilling Proj., 78, 801-810

Hyndman,R.D., Davis,E.E. and Wright,J.A. 1979. The measurement of marine geothermal heat flow by a multipenetration probe with digital acoustic telemetry and insitu thermal conductivity. Mar.Geophys.Res., 4, 181-205

Hyndman,R.D., Fluck,P., Mazzotti,S. and three others. 2005. Current tectonics of the northern Canadian Cordillera. Can.J.Earth Sci., 42, 1117-1136

Hyndman,R.D., Foucher,J.P., Yamano,M. and Fisher,A. 1992. Deep sea bottom-simulating reflectors: calibration of the base of the hydrate stability field as used for heat flow estimates. Earth,Planet.Sci.Lett., 109, 289-301

Hyndman,R.D., Jessop,A.M., Judge,A.S. and Rankin,D.S. 1979. Heat flow in the Maritime Provinces of Canada. Can.J.Earth Sci., 16, 1154-1165

Hyndman,R.D., Langseth,M.G. and Von Herzen,R.P. 1984. A review of the deep sea drilling project geothermal measurements through leg 71. Init.Rept.Deep Sea Drilling Proj., 78, 813-823

Hyndman,R.D., Lewis,T.J., Wright,J.A., and three others. 1982. Queen Charlotte Fault Zone - heat flow measurements. Can.J.Earth Sci., 19, 1657-1669

Hyndman,R.D., Muecke,G.K. and Aumento,F. 1974. Deep drill 1972. Heat flow and heat production in Bermuda. Can.J.Earth Sci.,11,809-818

Hyndman,R.D., Rogers,G.C., Bone,M.N., and seven others. 1978. Geophysical measurements in the region of the Explorer Ridge off western Canada. Can.J.Earth Sci., 15, 1508-1525

Issler,D.R. and Beaumont,C. 1986. Estimates of terrestrial heat flow in offshore eastern Canada: discussion. Can.J.Earth Sci.,, 23, 2083-2085

Issler,D.R., Beaumont,C., Willett,S.D., and others. 1990. Preliminary evidence from apatite fission-track data concerning the thermal history of the Peace River Arch region, Western Canada Sedimentary Basin. Bull.Can.Petr.Geol., 38, 250-269

Jessop,A.M. 1964. Geothermal research in Canada. Can.Min.Met.Bull. 67

Jessop,A.M. 1964. A lead-compensated thermistor probe. J.Sci Inst., 41, 503-504

Jessop,A.M. 1968. Three measurements of heat flow in eastern Canada. Can.J.Eartth Sci., 5, 61-68

Jessop,A.M. 1970. The effect of environment on divided bar measurements. Tectonophysics, 10, 39-49

Jessop,A.M. 1971. The distribution of glacial perturbation of heat flow in Canada. Can.J.Earth Sci., 8, 162-166

Jessop,A.M. 1972. Heat flow and permafrost. Bull.Can.Inst.Min.Met., 65, 45-48

Jessop,A.M. 1973. Terrestrial heat flow and permafrost. Nat.Res.Coun.technical Memorandum 108, 57-59

Jessop,A.M. 1976. Geothermal energy from sedimentary basins. Earth Physics Br., Geothermal Series 8, 10pp

Jessop,A.M. 1976. Geothermal studies in Canada. In - Geophysics of the Americas, Ed.Tanner & Dence, Publ.Earth Phys.Br., 46, 3, 70-73

Jessop,A.M. 1983. The essential ingredients of a continental heat flow determination. Zbl.Geol.Palaont., 1, 70-79

Jessop,A.M. 1987. Estimation of lateral water flow in an aquifer by thermal logging. Geothermics, 16, 117-126

Jessop,A.M. 1989. Hydrological distortion of heat flow in sedimentary basins. Tectonophysics, 164, 211-218

Jessop,A.M. 1990. Thermal geophysics. Elsevier Publishing Co., 305pp

Jessop,A.M. 1990. Comparison of industrial and high-resolution thermal data in a sedimentary basin. Pageoph, 133, 251-267

Jessop,A.M. 1992. Thermal imput from the basement of the Western Canada Sedimentary Basin. Bull.Can.Soc.Petrol.Geol. 40, 198-206

Jessop,A.M. and Judge,A.S. 1971. Five measurements of heat flow in southern Canada. Can.J.Eartth Sci., 8, 711-716

Jessop,A.M. and Judge,A.S. 1975. Temperature and heat flux measurements through permafrost as a geophysical tool. Assoc.Com.Geotech.Res., Technical Memorandum 114, 17-27

Jessop,A.M. and Judge,A.S. 1975. Temperature measurements in boreholes for the mining industry. In - Borehole Geophysics applied to metallic mineral prospecting, a review. Geol.Surv. Can. Paper 75-31, 55-65

Jessop,A.M. and Lewis,T.J. 1978. Heat flow and heat generation in the Superior Province of the Canadian Shield. Tectonophysics, 50, 55-77

Jessop,A.M. and Majorowicz,J.A. 1994. Fluid flow and heat transfer in sedimentary basins. In - Geofluids: Origin, Migration and Evolution of Fluids in Sedimentary Basins, Geol.Soc. Spec.Publ.78, 43-54

Jessop,A.M. and Vigrass,L.W. 1989. Geothermal measurements in a deep well at Regina, Saskatchewan. J.Volcan.Geothermal Res., 37, 151-166

Jessop,A.M., Allen,V.S. and eight others. 2005. The Canadian geothermal data compilation. Geological Survey of Canada, Open File 4887

Jessop,A.M., Hobart,M.A. and Sclater,J.G. 1976. The world heat flow data collection - 1975. Earth Physics Br., Geothermal Series 5, 125pp

Jessop,A.M., Lewis,T.J., Judge,A.S., and two others. 1984. Terrestrial heat flow in Canada. Tectonophysics, 103, 239-261

Jessop,A.M., Robertson,P.B. and Lewis,T.J. 1979. A brief summary of the thermal conductivity of crystalline rocks. Atomic Energy Can., Tech Rept. TR-12

Jessop,A.M., Souther,J.G., Lewis,T.J. and Judge,A.S. 1984. Geothermal measurements in northern British Columbia and southern Yukon Territory. Can.J.Earth Sci., 21, 599-608

Jessop.A.M., Lewis,T.J. and Drury,M.J. 1991. Terrestrial heat flow in Canada. In - Terrestrial heat flow and the lithosphere Structure, Ed. Cermak,V. and Rybach,L., Springer Verlag, 1-22

Jones,F.W. and Majorowicz,J.A. 1987. Regional trends in radiogenic heat generation in the Precambrian basement of the Western Canadian Basin. Geophys.Res.Lett., 14, 268-271

Jones,F.W. and Pascal,F. 1994. Numerical model calculations of the effects of grain size and orientations on the thermal conductivities of composites. Geothermics, 23, 365-371.

Jones,F.W. and Pascal,F. 1995. Numerical calculations of the thermal conductivities of composites - a 3-D model. Geophysics, 60, 1038-1050.

Jones,F.W. and Sydora,R.D. 1980. Numerical calculations of the perturbation of normal heat flow by topography and local conductivity structure. J.Volcan.Geoth.Res., 8, 285-295

Jones,F.W., Kushigbor,C., Lam,H.L., and two others. 1984. Estimates of terrestrial thermal gradients and heat flow variations with depth in the Hinton-Edson area of the Alberta Basin derived from petroleum bottom-hole temperature data. Geophys.Prospecting, 32 1111-1130

Jones,F.W., Majorowicz,J.A. and Embry,A.F. 1989. A heat flow profile across the Sverdrup Basin, Canadian Arctic Islands. Geophysics, 54, 171-180

Jones,F.W., Majorowicz,J.A. and Lam,H.L. 1985. The variation of heat flow density with depth in the Prairies Basin of western Canada. Tectonophysics, 121, 35-44

Jones,F.W., Majorowicz,J.A., Dietrich,J. and Jessop,A.M. 1990. Geothermal gradients and heat flow in the Beaufort-Mackenzie Basin, Arctic Canada. Pageoph, 134, 473-483

Jones,F.W., Majorowicz,J.A., Embry,A.F. and Jessop,A.M. 1990. Geothermal gradients and terrestrial heat flow along a south-north profile in the Sverdrup Basin, Canadian Arctic Archipelago. Geophysics, 55, 1105-1107

Jones,F.W., Majorowicz,J.A., Linville,A. and Osadetz,K.G. 1986. The relationship of hydrocarbon occurrences to geothermal gradients and time-temperature indices in mesozoic formations of southern Alberta. Bull.Can.Petrol.Geol., 34, 2, 226-239

Jones,F.W., Pascal,F. and Ertman,M.E. 1993. The thermal regime of a three-dimensional subducting lithospheric slab and its electromagnetic response: a numerical model. Tectonophysics, 222, 35-48

Jones,F.W., Rahman,M., Majorowicz,J.A. and Lam,H.L. 1983. A study of thermal properties of sedimentary rocks of western Canada. Earth Physics Br., Open File 83-7, 1079pp

Jones.F.W., Lam,H.L. and Yuen,D. 1982. A study of existing temperature data from Canadian sedimentary basins. Earth Physics Br., Open File 82-22, 107pp

Judge,A.S. 1971. Geothermal measurements in a sedimentary basin. Thesis, Ph.D., University of Western Ontario

Judge,A.S. 1973. The prediction of permafrost thickness. Can.Geotech.J., 10, 1-11

Judge,A.S. 1973. Deep temperature observations in the Canadian North. North American Contr. Second Int. Permafrost Conf., NAS/NRC, Washington, 35-41

Judge,A.S. 1973. Measurement of thermal conductivity of earth materials. Proc. Symp. Thermal Regime and Meas. in Permafrost, Tech Memo. 108, Assoc. Comm. Geotech. Res. NRC. 26-31

Judge,A.S. 1973. Ground temperature measurement using thermistors. Proc. Symp. Thermal Regime and Meas. in Permafrost, Tech Memo. 108, Assoc. Comm. Geotech. Res. NRC. 13-22

Judge,A.S. 1973. Selected bibliography of heat flow measurements and subsurface temperatures in the Canadian Arctic and Alaska. Proc. Symp. Thermal Regime and Meas. in Permafrost, Tech Memo. 108, Assoc. Comm. Geotech. Res. NRC. 54-59

Judge,A.S. 1974. Geothermal measurements in northern Canada. Proc. Symp. Geology of the Canadian Arctic GAC/CSPG. 301-312

Judge,A.S. 1975. Geothermal studies in the Mackenzie Valley by the Earth Physics Branch. Earth Physics Br., Geothermal Series 2, 12pp

Judge,A.S. and Bawden,W. 1987. Geothermal contours and geothermal gradients. In - Marine science atlas of the Beaufort Sea, geology and geophysics. Ed Pelletier,B.R. Geol.Survey Can. Misc.Rept.m, 40, 6-7

Judge,A.S. and Beck,A.E. 1967. An anomalous heat flow layer at London, Ontario. Earth,Planet.Sci.Lett., 3, 167-170

Judge,A.S. and Beck,A.E. 1973. Analysis of heat flow data - several boreholes in a sedimentary basin. Can.J.Earth Sci.,10, 1494-1507

Judge,A.S. and Jessop,A.M. 1978. Heat flow north of 60N. In - Arctic Geophysical Review, Ed.Sweeney, Publ.Earth Phys.Br., 45, 4, 25-33

Judge,A.S. and Majorowicz,J.A. 1992. Geothermal conditions for gas hydrate stability in the Beaufort-Mackenzie area: the global change aspect. Palaeogeog.Palaeoclim.Palaeoecol., 98, 251-263

Judge,A.S., Duguid,A., Taylor,A.E. and Allen,V. 1989. The automatic well temperature measuring system installed at Cape Allison C-47, offshore well, Arctic Islands of Canada. J.Can.Petrol.Tech., 28, 89-94

Judge,A.S., Hunter,J.A., Good,R.L., Cowan,J. and Robb,G. 1976. Thermistor cable installation in permafrost materials with a water-jet drilling method. Geol.Surv.Can., Paper 76-1A, 479-480

Judge,A.S., Smith,S.L. and Majorowicz,J.A. 1994. The current distribution and thermal stability of natural gas hydrates in the Canadian polar regions. Proc.Fourth Intl.Offshore and Polar Engng Cong., Osaka, Japan, 307-314

Judge,A.S., Taylor,A.E. and Burgess,M.M. 1979. Canadian geothermal data collection - northern wells 1977-78. Earth Physics Br., Geothermal Series 11, 187pp

Judge,A.S., Taylor,A.E. and Rutledge,L. 1979. A supplement to the Canadian geothermal data collection - northern wells 1977-78. Earth Physics Br., Open File 79-13, 64pp

Judge,A.S., Taylor,A.E., Burgess,M. and Allen,V.A. 1981. Canadian geothermal data collection - northern wells 1978-80. Earth Physics Br., Geothermal Series 12, 190pp

Kamp,G van der. 1982. Interactions between heat flow and groundwater flow - a review. Earth Physics Br., Open File 82-19, 87pp

Kamp,G.van der and Bachu,S. 1989. Use of dimensional analysis in the study of thermal effects of various hydrological regimes. In - Hydrological regimes and their subsurface effects. Ed. Beck,A.E., Garven,G, Stegena,L. Am.Geophys.Un., Geophys.Momogr. 47, 23-28

Keen,C.E. and Lewis,T.J. 1982. Radiogenic heat production in sediments from the continental margin of eastern North America - implications for hydrocarbon generation. Bull.Am.Ass.Petrol.Geol., 66, 1402-1407.

Kennedy,P.L. and Woodbury,A.D. 2000. Minimum relative entropy: theory and application to surface temperature reconstruction from borehole surface measurements. Geophys. Res. Lett., 27, 3081-3084

Lachenbruch,A.H. 1957. Thermal effects of the ocean on permafrost. Bull.Geol.Soc.Am., 68, 1515-1529

Lachenbruch,A.H. and Marshall,B.V. 1969. Heat flow in the Arctic. Arctic, 22, 300-311

Lam,H.L., Jones,F.W. and Majorowicz,J.A. 1985. A statistical analysis of bottom-hole temperature data in southern Alberta. Geophysics, 50, 677-684

Lam.H.L. and Jones,F.W. 1984. Geothermal gradients of Alberta in western Canada. Geothermics, 13, 181-192

Langseth,M.G., Hyndman,R.D., Becker,K., and two others. 1984. The hydrological regime of isolated sediment ponds in mid-oceanic ridges. Init.Rept.Deep Sea Drilling Proj., 78, 825-837

Law,L.K., Paterson,W.S.B. and Whitham,K. 1965. Heat flow determinations in the Canadian Arctic Archipelago. Can.J.Earth Sci., 2, 59-71

Leblanc,Y., Pascoe,L.J. and Jones,F.W. 1981. The temperature stabilisation of a borehole. Geophysics, 46, 1301-1303

Leith,T.H. 1952. Heat flow at Kirkland Lake. Trans.Am.Geophys.Un., 33, 435-443

Lewis,J.F. and Hyndman,R.D. 1976. Oceanic heat flow measurements over the continental margins of eastern Canada. Can.J.Earth Sci., 13, 1031-1038

Lewis,J.F. and Jessop,A.M. 1981. Heat flow in the Garibaldi Volcanic Belt, a possible Canadian geothermal energy resource area. Can.J.Earth Sci., 18, 366-375

Lewis,T.J. 1969. Terrestrial heat flow at Eldorado, Saskatchewan. Can.J.Earth Sci., 6, 1191-1197

Lewis,T.J. 1974. Heat production measurement in rocks using a gamma ray spectrometer with a solid state detector. Can.J.Earth Sci.,11, 526-532

Lewis,T.J. 1975. A geothermal survey at Lake Dufault, Quebec. Thesis, Ph.D. Univ Western Ontario

Lewis,T.J. 1976. Heat generation in the Coast Range Complex and other areas of British Columbia. Can.J.Earth Sci., 13, 1634-1642

Lewis,T.J. 1983. Bottom water temperature variations as observed and recorded in the bottom sediments, Alice Arm and Douglas Channel, British Columbia. Proc. Workshop kitimat Marine environment, Ed. MacDonald,R.W., Can.Tech Rept. Hydrography, Ocean Sci., 18, 138-161

Lewis,T.J. 1984. Geothermal energy from Penticton Tertiary Outlier, British Columbia, an initial assessment. Can.J.Earth Sci., 21 181-188

Lewis,T.J. 1987. Heat flow and heat generation in the Churchill Province of the Canadian Shield, and their paleotectonic significance: discussion. Tectonophysics, 132, 343-347

Lewis,T.J. 1987. Measuring the thermal conductivity and heat generation of sedimentary units. In - Hydrology of sedimentary basins: application to exploration and exploitation. Proc Third Can/Am.Conf Hydrogeol., 140-142

Lewis,T.J. 1989. Canadian Cordillera geothermal data base. In - Geophysics of North America, Ed. Hittelman,a.m. et al ,Natl.Geophys. Data Centre, NOAA

Lewis,T.J. 1989. Heat flux profile across Lithoprobe transect B2. Trans.Am.Geophys.Un., EOS, 70, 1989

Lewis,T.J. 1991. Heat flux in the Canadian Cordillera. In - Neotectonics of North America, Ed. Slemmons, Engdahl, Zoback, and Blackwell, Geol.Soc.Am., Decade Map Volume 1, 445-456

Lewis,T.J. 1998. The effect of deforestation on ground surface temperatures. Glo., Planet. Change, 18, 1-13

Lewis,T.J. and Beck,A.E. 1977. Analysis of heat flow data - detailed observations in many holes in a small area. Tectonophysics, 41, 41-59

Lewis,T.J. and Bentkowski,W.H. 1988. Potassium, uranium, and thorium concentrations of crustal rocks: a data file. Geol.Surv.Can., Open File 1744, 9pp + tables

Lewis,T.J. and Bentkowski,W.H. 1991. Blocky sediments in Bute and Knight Inlets, British Columbia. Geol.Surv.Can, Paper 91-1A, 303-308

Lewis,T.J. and Skinner,W. 2003. Inferring climate change from underground temperatures: apparent climatic stability and apparent climatic warming. Earth Interactions, 7, 1-9

Lewis,T.J. and Souther,J.G. 1978. Meager Mountain, B.C. - a possible geothermal energy resource. Earth Physics Br., Geothermal Series 9, 17pp

Lewis,T.J. and Wang,K. 1992. Clues to past climate found down a borehole. Earth in Space, 5, 10-12

Lewis,T.J. and Wang,K. 1992. Geopthermal research related to past climate. Trans. Am. Geophys. Un., Eos, 73,265-269

Lewis,T.J. and Wang,K. 1992. Influence of terrain on bedrock temperatures. Palaeogeog. Palaeoclim. Palaeoecol., 98, 87-100

Lewis,T.J. and Wang,K. 1998. Geothermal evidence for deforestation induced warming: implications for the climatic impact of land development. Geophys.Res.Lett., 25, 535-538

Lewis,T.J. and Werner,L. 1982. Geotherma gradients on the west side of Okanagan Lake, B.C. Earth Physics Br., Open File 82-6.

Lewis,T.J. and Werner,L. 1982. Geothermal gradients on the west side of Okanagan Lake, B.C. Earth Physics Br., Open File 82-6, 58 pp

Lewis,T.J. and Woodsworth,G.H. 1981. Heat generation in the northern Hogem Batholith and nearby plutons of McConnell Creek map area, B.C. Geol.Surv.Can. Paper 81-1B,, 163-164

Lewis,T.J., Allen,V.A., Taylor,A.E. and Jessop,A.M. 1979. Temperature observations during drilling of two 400 m wells in the Coryell intrusives north of Grand Forks, British Columbia, 1978. Earth Physics Br., Open File 79-4, 24 pp

Lewis,T.J., Bennetts,H., Allen,V.S. and Chan,F. 1984. Uranium, thorium and Potassium concentrations and heat generated in samples of crustal rocks. Earth Physics Br., Open File 84-15, 163pp

Lewis,T.J., Bentkowski,W.H. and Hyndman,R.D. 1992. Crustal temperatures near the Southern Canadian Cordillera Transect. Can.J.Earth Sci., 29, 1197-1214

Lewis,T.J., Bentkowski,W.H. and Hyndman,R.D. 1993. Crustal reflectors, metamorphic reactions and crustal temperatures in the southern Canadian Cordillera. Tectonophysics, 225, 57-61

Lewis,T.J., Bentkowski,W.H. and Hyndman,R.D. 1993. Crustal temperatures near the Lithoprobe southern Canadian Cordilleran transect. Can.J.Earth Sci., 29, 57-61

Lewis,T.J., Bentkowski,W.H. and Wright,J.A. 1991. Thermal state of the Queen Charlotte Basin, British Columbia: warm. In - Evolution and hydrocarbon potential of the Queen Charlotte Basin, British Columbia. Ed.Woodsworth,G., Geol.Surv.Paper 90-10, 489-506

Lewis,T.J., Bentkowski,W.H., Bone,M. and Wright,J.A. 1989. Note on the thermal structure of Queen Charlotte Basin, British Columbia. Geol.Surv.Can., Paper 89-1H, 121-125

Lewis,T.J., Bentkowski,W.H., Bone,M., and two others. 1988. Geothermal studies in the Queen Charlotte Basin, British Columbia. Geol.Surv.Can. Paper88-1E, 247-249

Lewis,T.J., Bentkowski,W.H., Davis,E.E., and two others. 1988. Subduction of the Juan de Fuca Plate: thermal consequences. J.Geophys.Res., 93, 15207-15225

Lewis,T.J., Bentkowski,W.H., Davis,E.E., and two others. 1989. Thermal structure of the northern (Canadian) Cascades. Proc.Conf.Geol.Geophys.Tectonic setting of the Cascade Range. U.S.Geol.Surv. Open File 89-178, 104-121

Lewis,T.J., Hyndman,R.D. and Fluck,P. 2003. Heat flow, heat generation, and crustal temperature in the Northern Canadian Cordillera: thermal control of tectonics. J.Geophys.Res., 108, B6, 2316

Lewis,T.J., Jessop,A.M. and Judge,A.S. 1985. Heat flux measurements in southwestern British Columbia: the thermal consequences of plate tectonics. Can.J.Earth Sci., 22, 1262-1273

Lewis,T.J., Judge,A.S. and Souther,J.G. 1979. Possible geothermal sources in the Coast Plutonic Complex of southern British Columbia. Pageoph, 117, 172-179

Lewis,T.J., Lowe,C. and Hamilton,T.S. 1997. Continental signature of a ridge-trench-triple junction: Northern Vancouver Island. J.Geophys.Res., 102, 7767-7781

Lewis,T.J., Villinger,H. and Davis,E.E. 1993. Thermal conductivity measurement of rock fragments using a pulsed needle probe. Can.J.Earth Sci.,30, 480-485

Lewis,T.J., Wang,K. and Majorowicz,J.A. 1994. Regional differences in past climates: evidence from temperature logs in Canada. Proc.7th Intl.Symp. Observations of the continental crust through drilling, Santa Fe, 185-188

Lister,C.R.B., Sclater,J.G., Davis,E.E. and Villinger,H. 1990. Heat flow maintained in ocean basins of great age: investigations in the north-equatorial west Pacific. Geophys.J.Int., 102, 603-630

Louden,K.E. and Wright,J.A. 1989. Marine heat flow data: a new compilation of observations and brief review of its analysis. In - CRC handbook of seafloor heat flow, Ed. Wright,J.A., Louden,K.E., CRC Press, 3-67

Louden,K.E., Dadey,K.A. and Srivastava,S.P. 1989. Heat flow measurements at Hole 646A. In - Proceedings of the Ocean Drilling Program; Baffin Bay and Labrador Sea, Leg 105, 923-931

Louden,K.E., Leger,G. and Hamilton,N. 1990. Marine heat flow observations on the Canadian Arctic Continental Shelf and Slope. Mar.Geol., 93, 267-288

Louden,K.E., Sibuet,J.C. and Foucher,J.P. 1991. Variations in heat flow across the Goban Spur and Galicia Bank continental margins. J.Geophys.Res., 96, 16131-16150

Louden,K.E., Sibuet,J.C. and Harmegnies,F. 1997. Variations in heat flow across the ocean - continent transition in the Iberia abyssal plain. Eart Planet.Sci Lett., 151, 233-254.

Louden,K.E., Wallace,D.O. and Courtney,R.C. 1987. Heat flow and depth versus age for the Mesozoic northwest Atlantic Ocean: results from the Sohm Abyssal Plain and implications for the Bermuda Rise. Earth,Planet.Sci.Lett., 83, 109-122

Majorowicz,J.A. 1989. The controversy over the significance of hydrodynamic effect on heat flow in the Prairies Basin. In - Hydrological regimes and their subsurface effects. Ed. Beck,A.E., Garven,G, Stegena,L. Am.Geophys.Un., Geophys.Monogr. 47, 101-105

Majorowicz,J.A. 1993. Climate change inferred from analysis of borehole temperatures: first results from Alberta Basin, Canada. Pageoph, 140, 655-666

Majorowicz,J.A. 1996. Accelerating ground warming in the Canadian Prairie Provinces: is it a result of global warming?. Pageoph, 147, 1-24

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

Majorowicz,J.A. 1998. A constraint to the methane gas hydrate stability from the analysis of thermal data in the northern Canadian sedimentary basins - Arctic Archipelago case. Proc. 7th Intnl Conf. Permafrost, Yellowknife, Nwt, Canada, Nordicana, Univ. Laval, 703-709

Majorowicz,J.A. and Deitrich,J.R. 1989. Comparison of the geothermal and organic maturation gradients of the central and southwestern Beaufort-Mackenzie Basin, Yukon and Northwest Territories. Geol.Surv.Can., Paper 89-1G, Frontier Geoscience Program, 63-67

Majorowicz,J.A. and Dietrich,J.R. 1989. Comparison of the thermal and organic maturation gradients of the central and southwestern Beaufort-Mackenzie Basin, Yukon and Northwest Territories. In - Current Research, Geol Surv.Can.Paper 89-1G, 63-67

Majorowicz,J.A. and Embry,A. 1998. Present heat flow and paleogeothermal regime in the Canadian Arctic margin - analysis of industrial thermal data and coalification gradients. In - Heast flow and structure of the lithosphere, Ed: Cermak,V., Tectonophysics, 291, 141-159

Majorowicz,J.A. and Gough,D.I. 1994. A model of crustal conductive structure in the Canadian Cordillera. Geophys.J.Int., 117,301-312

Majorowicz,J.A. and Hannigan,P. 2000. Stability zone of natural gas hydrates in a permafrost-bearing region of the Beaufort-Mackenzie Basin: study of a feasible energy source. Natural Resour.Res.,9, 3-25

Majorowicz,J.A. and Hannigan,P. 2000. Natural gas hydrates in the offshore Beaufort-Mackenzie Basin - study of a feasible energy source ii. Natural Resour.Res.,9, 201-214

Majorowicz,J.A. and Jessop,A.M. 1981. Present heat flow and a preliminary geothermal history of the Central Prairies Basin, Canada. Geothermics, 10, 81-93

Majorowicz,J.A. and Jessop,A.M. 1981. Regional heat flow patterns in the Western Canadian Sedimentary Basin. Tectonophysics, 74, 209-238

Majorowicz,J.A. and Jessop,A.M. 1993. Relation between basement heat flow and thermal state of the sedimentary succession of the Alberta Plains. Bull.Can.Petr.Geol., 41, 358-368

Majorowicz,J.A. and Morrow,D.W. 1998. Subsurface temperature and heat flow - Yukon and Northwest territories. Geol.Surv.Can., Open File 3626, 6pp + figs.

Majorowicz,J.A. and Osadetz,K.G. 2001. Gas hydrate volume and distribution in Canada. Bull.Am.Assoc.Petrol.Geol., 85, 1211-1230

Majorowicz,J.A. and Osadetz, K.G. (2008). Cordilleran Intermontane thermotectonic history and implications, for neotectonic structure and petroleum systems, British Columbia, Canada. Int. J. Earth Sci, (Geol. Rundshau) 97, 269-287

Majorowicz,J.A. and Safanda,J. 1998. Ground surface temperature history from inversion of underground temperatures - a case study of the Western Canadian Sedimentary Basin. Tectonophysics, 291, 287-298

Majorowicz,J.A. and Safanda,J. 2001. Composite surface temperature history from simultaneous inversion of borehole temperatures in Western Canadian Plains. In - Inference of climate change from geothermal data, Ed: Beltrami,H, Harris,R.N., Glob.Planet.Change, 29, 231-239

Majororwicz,J.A. and Safanda,J. 2005. Measured versus simulated transkents of temperature logs - a test of borehole climatology. J.Geophys. Eng., 2, 1-8

Majorowicz,J.A. and Skinner,W.R. 1997. Recent and pre-instrumental climatic conditions as reconstructed from temperatire logs in western and northern Canada. AMS trans., Global Change Symposium, Long Beach, California, Paper 15.1.

Majorowicz,J.A. and Skinner,W.R. 1997. Potential causes of differences between ground and surface air temperature warming across different ecozones in Alberta, Canada. Glob., Planet Change, 15, 79-91

Majorowicz,J.A. and Skinner,W.R. 1997. Anomalous ground warming vs surface air warming in the Canadian Prairie provinces. Climat.Change, 35, 485-500

Majorowicz,J.A. and Skinner,W.R. 2001. Reconstruction of the surface warming history of western interior canada from borehole temperature profiles and other climate information. Clim.Res., 16, 157-167

Majorowicz,J.A. and Smith,S.L. 1999. Review of ground temperatures in the Malik field area: a constraint to the methane hydrate stability. In - Sci results JAPEX/JNOC/GSC Malik 2L-38 Gas Hydrate REs. Well, Ed Dallimore et al, 45-56.

Majorowicz,J.A. and Smith,S.L. 1999. Review of ground temperatures in the Mallik field area: a constraint to the methane hydrate stability. In - Scientific results from JAPEX/JNOC/GSC Mallik 2L-38 gas hyfdrate well. Mackenzie Delta, Northwest Territories, Canada. Geol.Survey Can Bull.544, 45-56

Majorowicz,J.A., Garven,G., Jessop,A.M. and Jessop,C. 1999. Present heat flow along a profile across the Western Canada Sedimentary Basin: the extent of hydrodynamic influence. In - Geothermics in basin analysis, Ed. Forster,A and Merriam,D.F. Kluwer/Plenum, 61-79

Majorowicz,J.A., Gough,D.I. and Lewis,T.J. 1993. Correlation between the depth to the lower-crustal high conductive layer and heat flow in the Canadian Cordillera. Tectonophysics, 225, 49-56

Majorowicz,J.A., Gough,D.I. and Lewis,T.J. 1993. Electrical conductivity and temperature in the Canadian Cordilleran crust. Earth,Planet.Sci.Lett., 115,, 57-64

Majorowicz,J.A., Hannigan,P.K. and Osadetz,K.G. 2002. Study of the natural gas hydrate Trap Zone and the methane hydrate potential in the Sverdrup Basin, Canada. Natural Resour.Res., 11, 79-96

Majorowicz,J.A., Jessop,A.M. and Judge,A.S. 1996. Geothermal regime. In - Geological atlas of the Beaufort Mackenzie area, Ed J.Dixon, Geol.Surv.Can. Report 59, 33-37.

Majorowicz,J.A., Jones,F.W. and Ertman,M.E. 1989. Subsurface conductive and hydrological related thermal effects in the area of the crustal electrical conductors of the Williston Basin. In - Hydrological regimes and their subsurface effects. Ed. Beck,A.E., Garven,G, Stegena,L. Am.Geophys.Un., Geophys.Momogr. 47, 149-150

Majorowicz,J.A., Jones,F.W. and Ertman,M.E. 1989. Model of terrestrial thermal effects in the area of the crustal electrical conductors of the Williston Basin. Can.J.Explor.Geophys., 25, 45-49

Majorowicz,J.A., Jones,F.W. and Jessop,A.M. 1986. Geothermics of the Williston Basin in Canada in relation to hydrodynamics and hydrocarbon occurrences. Geophysics, 51, 3, 767-779

Majorowicz,J.A., Jones,F.W. and Jessop,A.M. 1988. Preliminary geothermics of the sedimentary basins in the Yukon and Northwest territories (60-70 degrees north) - estimates from petroleum bottom-hole temperature data. Bull.Can.Petrol.Geol., 36, 39-51

Majorowicz,J.A., Jones,F.W. and Osadetz,K.G. 1988. Heat flow environment of the electrical conducting anomalies in the Williston Basin, and occurrences of hydrocarbons. Bull.Can.Petrol.Geol., 36, 86-90

Majorowicz,J.A., Jones,F.W., Ertman,M.E., and two others. 1990. The relationship between thermal maturation gradients, geothermal gradients and estimates of thickness of the eroded foreland section, southern Alberta Plains, Canada. Marine Petro.Geol., 7, 138-152

Majorowicz,J.A., Jones,F.W., Lam,H.L. and Jessop,A.M. 1984. The variability of heat flow both regional and with depth in southern Alberta, Canada - effect of groundwater flow. Tectonophysics, 106, 1-29,

Majorowicz,J.A., Jones,F.W., Lam,H.L. and Jessop,A.M. 1985. Regional variations of heat flow differences with depth in Alberta, Canada. Geophys.J.R.Astr.Soc., 81, 479-487

Majorowicz,J.A., Jones,F.W., Lam,H.L. and Jessop,A.M. 1985. Terrestrial heat flow and geothermal gradients in relation to hydrodynamics in the Alberta Basin, Canada. J.Geodyn., 4, 265-283

Majorowicz,J.A., Jones,F.W., Macqueen,R.W. and Ertman,M.E. 1989. The bearing of heat flow data on the nature of fluid flow in the Keg River Barrier - Pine Point ore field region, Canada,. Econ.Geol., 84, 708-714

Majorowicz,J.A., Judge,A.S. and Jones F.W. 1990. Deep subpermafrost thermal regime in the Mackenzie Delta Basin, northern Canada, analysis from petroleum bottom hole temperature data. Geophysics, 55, 362-371

Majorowicz,J.A., Rahman,M., Jones,F.W. and MacMillan,N.J. 1985. The paleogeothermal and present thermal regimes of the Alberta Basin and their significance for petroleum occurrence. Bull.Can.Petrol.Geol., 33, 12-21

Majorowicz,J.A., Safanda,J. and Skinner,W. 2002. East to west retardation in the onset of the recent warming across Canada from inversion of temperature logs. J.Geophys.Res., 107,2227, doi:10.1029/2001JB000519

Majorowicz,J.A., Safanda,J., Harris,R.N. and Skinner,W.R. 1999. Large ground surface temperature of the last three centuries inferred from boreholes temperatures in the southern Canadian Prairies, Saskatchewan. Glob. Planet. Change, 20, 227-241

Majorowicz,J.A., Skinner,W.R. and Safanda,J. 2004. Ground surface warming history in Northern Canada inferred from inversion of temperature logs ans comparison with other proxy climate reconstructions. Pure Appl.Geophys., 162, 109-128.

Majorowicz,J.A., Skinner,W.R. and Safanda,J. 2004. Large ground warmong in the Canadian Arctic inferred from inversion of temperature logs. Earth Plan.Sci.Lett., 221, 15-25, doi:10.1016/S0012-821X(04)00106-2.

Majorowicz, J.A., Skinner, W.R., and Safanda, J. (2004) Past surface temperature changes as derived from continental temperature logs-Canadian ans some global examples of application of a new tool in climate change studies. Advances in Geophysics 47, 114-175, Elsevier, Amsterdam

Mareschal,J.C. 1986. Comments on Models of an extending lithosphere and heat flow in the Basin and Range Province by A.H.Lachenbruch and J.H.Sass, and reply by A.H.Lachenbruch. J.Geophys.Res., 91, 7561-7569

Mareschal,J.C. 1991. Downward continuation of heat flow density data and thermal regime in eastern Canada. Tectonophysics, 194, 349-356

Mareschal,J.C. 1991. Determination of the past heat flow from subsidence data in intracontinental basins and passive margins. In - Terrestrial heat flow and the lithosphere Structure, Ed. Cermak,V. and Rybach,L., Springer Verlag, 70-85

Mareschal,J.C. and Jaupart,C. 2004. Variations of surface heat flow and lithospheric thermal structure beneath the North American craton. Earth,Planet.Sci.Lett., 223, 65-77

Mareschal,J.C. and Vasseur,G. 1992. Ground temperature history from two deep boreholes in central France. Palaeogeog.Palaeoclim.Palaeoecol., 98, 185-192

Mareschal,J.C., Hamdani,Y. and Jessup,D.M. 1989. Downward continuation of heat flow. Tectonophysics, 164, 129-137

Mareschal,J.C., Jaupart,C., Cheng,L.Z., and five others. 1999. Heat flow in the Trans-Hudson Orogen of the Canadian Shield: implications for Proterozoic continental growth. J.Geophys.Res., 104, 29007-29024

Mareschal,J.C., Jaupart,C., Gariepy,L.Z. and four others. 2000. Heat flow and deep thermal structure near the southeastern edge of the Canadian Shield. Can.J.Earth Sci., 37, 399-414

Mareschal,J.C., Nyblade,A., Perry,H.K.C., and two others. 2004. Heat flow and deep lithospheric thermal structure at Lac de Gras, Slave Province, Canada. Geophys. Res. Lett., 31, L12611

Mareschal,J.C., Pinet,C. et al. 1989. New heat flow density and radiogenic heat production data in the Canadian Shield and the Quebec Appalachians. Can.J.Earth Sc., 25, 845-852

Mareschal,J.C., Rolandone,F. and Bienfait,G. 1999. Heat flow variations in a deep borehole near Sept-Iles, Quebec, Canada: paleoclimatic interpretation and implications for regional heat flow estimates. Geophys.Res.Lett., 26, 2049-2052

Mathews,W.H. 1972. Geothermal data from the Granduc area, northern Coast Mountains of British Columbia. Can.J.Earth Sci., 9, 1333-1337

Michel, F.A., Allen, D.M. and Grant, M.B. (2001). Hydrogeochemistry and Geothermal Characteristics of the White Lake Basin, British Columbia, Canada. Geothermics, Fall Issue, 2001.

Misener,A.D. 1949. Temperature gradients in the Canadian Shield. Trans.Can.Inst.Min.Met., 52, 125-132

Misener,A.D. 1955. Heat flow and depth of permafrost at Resolute Bay, Cornwallis Island, N.W.T., Canada. Trans.Am.Geophys.Un., 36, 1055-1060

Misener,A.D. and Beck, A.E. 1960. The measurement of heat flow over land. In -Methods and Technoiques in Geophysics, Ed.Runcorn, Interscience, 11-61

Misener,A.D. and Thompson,L.G.D. 1950. Temperature gradients in Ontario and Quebec. Trans.Can.Inst.Min.Met., 53, 368-371

Misener,A.D., Bremner,P.C. and Hodgson,J.H. 1956. Heat flow measurements in permafrost at Resolute Bay, Northwest Territories. J.Roy.Astron.Soc.Can., 50, 14-24

Misener,A.D., Thompson,L.G.D. and Uffen,R.J. 1951. Terrestrial heat flow in Ontario and Quebec. Trans.Am.Geophys.Un., 32, 729-738

Mustonen,E.D. 1967. A micro-geothermal survey, Lake Dufault, Quebec. Thesis,M.Sc.,University of Western Ontario

Mwenifumbo,C.J., Bezys,R., Betcher,R. and Killeen,P.G. 1995. Borehole geophysical logs Manitoba (1992) (including logs from Grand Rapids and Winnipeg). Geol.Surv.Can., Open File 2734

Nagihara,S., Brooks,J.S. and three others. 2002. Application of marine heat flow data important in oil, gas exploration. Oil and gas J., 100,43-50

Nagihara,S., Sclater,J.G., Phillips,J.D. and six others. 1996. Heat flow in the western abyssal plain of the Gulf of Mexico: implications for thermal evolution of the old oceanic lithosphere. J.Geophys.Res., 101,2895-2913

Nielsen,S.B. 1987. Steady state heat flow in a random medium and the linear heat flow - heat production relationship. Geophys.Res.Lett., 14, 318-321

Nielsen,S.B. and Beck,A.E. 1989. Heat flow density values and paleoclimate determined from stochastic inversion of four temperature-depth profiles from the Superior Province of the Canadian Shield. Tectonophysics, 164, 345-359

Osadetz,K.G., Hannigan,P.K., Stasiuk,L.D. and six others. 1998. Williston Basin thermotectonics: variations in heat flow and hydrocarbon generation. In - Proc.Eighth Intl. Williston Basin Symp., Sask.Geol.Soc.,Spec.Publ.13, 147-165

Osadetz,K.G., Jones,F.W., Majorowicz,J.A. et al. 1992. Thermal history of the Cordilleran Foreland Basins in Western Canada: a review. In - Foreland basins and fold belts, Ed. Macqueen, R.W. and Leckie,D., AAPG Mem 55, 259-278

Osadetz,K.G., Kohn,B.P., Feinstein,S. and O'Sullivan,P.B. 2002. Thermal history of Canadian Williston Basin from apatite fission-track thermochronology - implications for petroleum systems and geodynamic history. Tectonophysics, 349, 221-249

Pascal,F. and Jones,F.W. 1994. Numerical calculations of the thermal conductivities of composites: a 2-D model. Geophys.J.Int., 118, 623,635

Paterson,W.S.B. and Law,L.K. 1966. Additional heat flow determinations in the area of Mould Bay, Arctic Canada. Can.J.Earth Sci., 3, 237-246

Perry,C., Jaupart,C., Mareschal,J.C. and Bienfait,G. 2006. Crustal heat production in the Superior Province, Canadian Shield, and in North America inferred from heat flow. J.Geophys.Res., 111, B04401.

Pinet,C., Jaupart,C., Mareschal,J.C., Gariepy,C., Bienfait,G. 1991. Heat flow and structure of the lithosphere in the eastern Canadian Shield. J.Geophys.Res., 96, 19941-19963

Powell,W.G., Chapman,D.S., Balling,N. and Beck,A.E. 1988. Continental heat flow density. In - Handbook of terrestrial heat-flow density determination, Ed.Haenel,R., Rybach,L., Stegena,L., Kluwer Acas Publ., 167-222

Pribnow,D.F.C., Davis,E.E. and Fisher,A.T. 2000. Borehole heat flow along the eastern flank of the Juan ed Fuca Ridge, including the effects of anisotropy and temperature dependence of sediment thermal conductivity. J.Geophys.Res., 105, 13449-13456.

Przybylak,R., Majorowicz,J.A. and seven others. 2005. Temperature changes in Poland from the 16th to the 20th centuries. Intl.J.Climatology, 25, 773-791

Pye,G.D. 1971. Heat flow measurements in Baffin Bay and the Labrador Sea. Thesis, M.Sc., Dalhousie University

Pye,G.D. and Hyndman,R.D. 1972. Heat-flow measurements in Baffin Bay and the Labrador Sea. J.Geophys.Res., 77, 938-944

Ranalli,G. 1991. Regional variations in lithosphere rheology from heat flow observations. In - Terrestrial heat flow and the lithosphere Structure, Ed. Cermak,V. and Rybach,L., Springer Verlag, 1-22

Rankin,D.S. 1974. Heat flow - heat production studies in Nova Scotia. Thesis, Ph.D., Dalhousie University, 188pp

Rankin,D.S. and Hyndman,R.D. 1971. Shallow water heat flow measurements in Bras d'Or Lake, Nova Scotia. Can.J.Earth Sci., 8, 96-101

Rao,R.U.M. and Jessop,A.M. 1975. A comparison of the thermal characters of shields. Can.J.Earth Sci., 12, 347-360

Ravenhurst,C.E., Willett,S., Dinelick,R.A. and Beaumont,C. 1994. Apatite fission track thermochronometry from central Alberta: implications for the thermal history of the western Canada Sedimentary Basin. J.Geophys.Res., 99, 20023-20041.

Reader,J.F. and Fairbank, B.D. 1983. Heat flow in the vicinity of the Meager Volcanic Complex, southwestern British Columbia. Trans.Geothermal REsoour.Coun., 7, 535-539

Rehault,J.P., Tisseau,C., Brunet,M.F. and Louden,K.E. 1990. Subsidence analysis on Sardinian marine and central Tyrrhenian Basin: thermal modelling and heat flow control: deep structure implications. J.Geodyn., 12, 269-310

Reiter,M.A. 1982. Extrapolated equilibrium bottom-hole temperatures for offshore petroleum drill tests in Atlantic Canada. Earth Physics Br., Open File 82-17, 11pp

Reiter,M.A. and Jessop,A.M. 1985. Estimates of terrestrial heat flow in offshore eastern Canada. Can.J.Earth Sci., 22, 1503-1517

Reiter,M.A. and Jessop,A.M. 1986. Estimates of terrestrial heat flow in offshore eastern Canada: reply. Can.J.Earth Sci.,, 23, 2085-2086

Rolandone,F., Jaupart,C., Mareschal,J.C. and four others. 2002. Surface heat flow, crustal temperatures nd matle heat flow in the Proterozoic Trans-Hudson Orogen, Canadian Shield. J.Geophys.Res., 107, 2341.

Rolandone,F., Mareschal,J.C. Jaupart,C. and three others. 2003. Heat flow in the western Superior Province of the Canadian Shield. Geophys Res.Lett., 30, 1637

Rona,P.A., Daveis,E.E. and Ludwig,R.J. 1998. Thermal properties of tag hydrothermal precipitates, Mid-Atlantic Ridge, and comparison with Middle Valley, Juan de Fuca Ridge. In - PRoc.Ocean Dr.Prog.,Sci.Results, 158, Ed Herzig et al. 329-335

Russell,J.K., Dipple,G.M. and Kopylova,M.G. 2001. Heat production and heat flow in the mantle lithosphere, Slave Craton, Canada. Phys.Earth Planet Interiors, 123, 27-44

Safanda,J., Szewczyk,J. and Majorowicz,J.A. 2003. Geothermal evidence of verylow glacial temperatures on a rim of the Fennoscandian ice sheet. In press

Sass,J.H. 1964. Evaluation of in-situ methods of measurement of thermal conductivity of rocks. Thesis, M.Sc., Univ.Western Ontario

Sass,J.H., Killeen,P.G. and Mustonen.E.D. 1968. Heat flow and surface radioactivity in the Quirke Lake Syncline near Elliot Lake, Ontario, Canada. Can.J.Earth Sci., 5, 1417-1428

Sass,J.H., Lachenbruch,A.H. and Jessop,A.M. 1971. Uniform heat flow in a deep hole in the Canadian Shield and its paleoclimatic implications. J.Geophys.Res., 76, 8586-8596

Saull,V.A., Clark,T.H., Doig,R.P. and Butler,R.B. 1962. Terrestrial heat flow in the St.Lawrence Lowland of Quebec. Can.Min.Met.Bull.,65,63-66

Schneider,R.V. and Roy,R.F. 1987. Investigations and interpretations of the vertical distribution of U, Th, and K: South Africa and Canada. Geophys.Res.Lett., 14,4 264-267

Shen,P.Y. and Beck,A.E. 1981. Determination of surface temperature history from borehole temperature gradients. J.Geophys.Res., 88, 7385-7493

Shen,P.Y. and Beck,A.E. 1981. Least squares inversion of borehole temperature measurements in functional space. J.Geophys.Res., 96, 19965-19979

Shen,P.Y. and Beck,A.E. 1983. Determination of surface temperature history from borehole temperature gradients. J.Geophys.Res., 88, 7385-7493.

Shen,P.Y. and Beck,A.E. 1992. Paleoclimatic change and heat flow density inferred from temperature data in the Superior Province on the Canadian Shield. Palaeogeog. Palaeoclim. Palaeoecol., 98, 143-165

Shen,P.Y., Pollack,H.N. and Huang,S. 1996. Inference of ground surface temperature history from borehole temperature data: a comparison of two inverse methods. Glob. Planet. Change, 14, 49-57.

Shen,P.Y., Wang,K. and Beck,A.E. 1990. Two-dimensional inverse modeling of crustal thermal regime with application to east European geotraverses. J.Geophys.Res.,95,19903-19925

Shen,P.Y., Wang,K. and Beck,A.E. 1991. Crustal thermal models along East European geotraverses: inverse solutions. Tectonophysics, 194, 363-385

Shen,P.Y., Wang,K., Beltrami,H. and Mareschal,J.C. 1992. A comparative study of inverse methods for estimating climatic history from borehole temperature data. Palaeogeog. Palaeoclim. Palaeoecol., 98, 113-127

Skinner,W.R. and Majorowicz,J.A. 1999. Regional climatic warming and associated Twentieth Century land cover changes in north-western North America. Climate Research, 12, 39-52

Smith,L., Forster,C. and Woodbury,A. 1989. Numerical simulation techniques and modeling advectively-disturbed thermal regimes. In - Hydrological regimes and their subsurface effects. Ed. Beck,A.E., Garven,G, Stegena,L. Am.Geophys.Un., Geophys.Momogr. 47, 1-5

Sweeney,J.F., Coles,R.L., Delaurier,J.M., abd others. 1978. Arctic geophysical review - a summary. Publ. Earth Physics Br., 45, 4, 101-108

Tatlor,A.E., Burgess,M., Judge,A.S., and Allen,V.S. 1982. Canadian Geothermal Data Collection - northern wells 1981. Earth Physics Br., Geothermal Series 13, 153 pp.

Taylor,A.E. 1978. Temperatures and heat flow in a system of cylindrical symmetry including a phase boundary. Earth Physics Br., Geothermal Series 7, 95pp

Taylor,A.E. 1988. A constraint to the Wisconsin glacial history, Canadian Arctic Archipelago. J.Quaternary Sci., 3, 15-18.

Taylor,A.E. 1991. Holocene paleoenvironmental reconstruction from deep ground temperatures: a comparison with paleoclimate derived from the 18O record in an ice core from the Agassiz Ice Cap, Canadian Arctic Archipelag. J.Gaciology, 37, 209-219.

Taylor,A.E. 1991. Marine transgression, shoreline emergence: evidence in seabed and terrestrial ground temperatures of changing relative sea levels, Arctic Canada. J.Geophys.Res., 96, 6893-6909

Taylor,A.E. and Allen,V.S. 1987. Shallow sediment temperature perturbations and sediment thermal conductivities. Can.J.Earth Sci., 24, 2223-2234

Taylor,A.E. and Judge,A.S. 1974. Canadian geothermal data collection - northern wells, 1955 to 1974. Earth Physics Br., Geothermal Series 1, 171 pp

Taylor,A.E. and Judge,A.S. 1975. Canadian geothermal data collection - northern wells, 1974. Earth Physics Br., Geothermal Series 3, 127pp

Taylor,A.E. and Judge,A.S. 1976. Canadian geothermal data collection - northern wells, 1975. Earth Physics Br., Geothermal Series 6, 142pp

Taylor,A.E. and Judge,A.S. 1977. Canadian geothermal data collection - northern wells, 1976-77.-. Earth Physics Br., Geothermal Series 10,

Taylor,A.E. and Judge,A.S. 1979. Permafrost studies in northern Quebec. Geogr.Phyr.Quat., 33, 245-251

Taylor,A.E. and Judge,A.S. 1980. Geothermal measurements and glacial surface temperature histories, northern Quebec, Canada. Am.Geophys.Un., Spring Mtg.Prog., 92

Taylor,A.E., Dallimore,S.R., Hyndman,R.D. and Wright,F. . Comparing the sensitivity of terrestrial and marine gas hydrtes to climate warming at the end of the last ice age.

Taylor,A.E., Judge,A.S. and Allen,V.S. 1986. Terrestrial heat flow from project Cesar, Alpha Ridge, Arctic Canada. J.Geodyn., 6, 137-176

Taylor,A.E., Judge,A.S. and Allen,V.S. 1989. Recovery off precise offshore permafrost temperatures from a deep geotechnical hole, Canadian Beaufort Sea. Geol.Surv.Can. Paper 89-1D, 119-123

Taylor,A.E., Judge,A.S. and Allen,V.S. 1989. The automatic well temperature measuring system installed at Cape Allison C-47, offshore well, Arctic Islands of Canada. Part 2 - data retrieval and analysis of the thermal regime. J.Can.Petrol.Tech., 28, 95-101

Thompson,J.E. 1948. The main ore zone at Kirkland Lake - geothermal gradient. Ont.Dept.Mines 57th Annual Rept.

Thompson,P.H., Judge,A.S. and Lewis,T.J. 1995. Thermal parameters in rock units of the Winter Lake - Lac de Gras area, central Slave Probince, Northwest Territories - implications for diamond genesis. Geol.Surv.Can. paper 95-1E, 125-135

Thompson,P.H., Judge,A.S. and Lewis,T.J. 1996. Thermal evolution of the lithosphere in the central Slave Province: inlications for diamond genesis. Geol.Surv.Can. Open File 3228, 151-160

Villinger,H. and Davis,E.E. 1987. A new reduction algorithm for marine heat flow measurements. J.Geophys.Res., 92, 12846-12856

Wang,K. 1992. Groundwater flow and geotemperature pattern. Encycl.Earth Syst.Science, 2, 441-453

Wang,K. and Beck,A.E. 1987. Heat flow measurement in lacustrine or oceanic sediments without recording bottom temperature variations. J.Geophys.Res., 92, 12837-12845

Wang,K. and Beck.A.E. 1989. An inverse approach to heat flow study in hydrologically active areas. Geophys.Res.Int., 98, 69-84

Wang,K. and Davis,E.E. 1992. Thermal effects of marine sedimentation in hydrothermally active areas. Geophys.J.Int., 110, 70-78

Wang,K. and Lewis,T.J. 1992. Geothermal evidence from Canada for a cold period before recent climatic warming. Science, 256, 1003-1005

Wang,K., Hyndman,R.D. and Davis,E.E. 1993. Thermal effects of sediment thickening and fluid expulsion in accretionary prisms: model and parameter analysis. J.Geophys.Res., 98, 9975-9984

Wang,K., Lewis,T.J. and Jessop,A.M. 1992. Climatic changes in central and eastern Canada inferred from deepborehole temperature data. Palaeogeog.Palaeoclim.Palaeoecol., 98, 129-141

Wang,K., Lewis,T.J., Belton,D.S., and Shen,P.Y. 1994. Differences in recent ground surface warming in eastern and western Canada: evidence from borehole temperatures. Geophys.Res.Lett., 21, 2689-2692

Wang,K., Shen,P. and Beck,A.E. 1989. A solution to the inverse problem of coupled hydrological and thermal regimes. In - Hydrological regimes and their subsurface effects. Ed. Beck,A.E., Garven,G, Stegena,L. Am.Geophys.Un., Geophys.Momogr. 47, 7-21

Wankiewicz,A. 1979. Temperature measurements under arctic streams. Pros.Symp.on Permafrost Geophysics, Tech.Memo.124, Ass.Com.Nat.Res.Coun.Can., Geotech.Res., 191-206

Weaver,J.G. 1967. Geothermal temperature measurements using oscillators. Thesis, M.Sc., Univ.Toronto

Woodroffe,D.A. 1984. Acquisition and testing of an integrated system to instrument an offshore well for the purpose of recording wellbore temperature. Earth Physics Br., Open File 84-25, 117pp

Wright,J.A. 1965. In-situ measurement of thermal conductivity of rocks. Thesis, M.Sc., Univ.of Toronto, 67pp+append

Wright,J.A. 1968. Geothermal investigations using in-situ techniques. Thesis, Ph.D., Univ.Toronto, 109pp

Wright,J.A. 1988. A microprocessor-based marine heat flow probe with solid-state data storage. In - CRC handbook of seafloor heat flow, Ed.Wright, and Louden, CRC Press, 121-134

Wright,J.A. and Garland,G.D. 1968. In-situ measurement of thermal conductivity in the presence of transverse anisotropy. J.Geophys.Res.,73, 5477-5484

Wright,J.A. and Louden,K.E. (Eds). 1988. CRC Handbook of seafloor heat flow. CRC Press., 323pp

Wright,J.A., Jessop,A.M., Judge,A.S. and Lewis,T.J. 1980. Geothermal measurements in Newfoundland. Can.J.Earth Sci., 17, 1370-1376

Yorath,C.J. and Hyndman,R.D. 1983. Subsidence and thermal history of Queen Charlotte Basin. Can.J.Earth Sci., 20, 135-159

Young,S. and Judge,A.S. 1985. A ground temperature data collection for northern Canada. Proc. McGill workshop on climate and thermal regimes in northern Canada,16p.

2. CANADIAN GEOTHERMAL ENERGY BIBLIOGRAPHY

Abdel-aal,O.Y. and Hall,J.M. 1978. Opaque mineral alteration states correlated with temperature in an active geothermal system. Nature, 272, 239-240

Acres Consulting Services .Ltd. and Nevin, Sadlier-Brown, Goodbrand,Ltd 1984. Regulatory and commercial aspects of geothermal energy development. Earth Phys.Br., Open File 84-12, 377pp

Acres Consulting Services Ltd. 1983. Low temperature geothermal energy applications. Rept.to Nat.Res.Coun., 159pp,

Acres Consulting Services Ltd. 1984. Study of mine air heating with geothermal energy. Earth Phys.Br., Open File 84-14, 66pp

Acres Consulting Services Ltd. 1984. Survey of geothermal energy in the Maritime Provinces. Earth Phys.Br., Open File 84-13, 139pp

Acres International Ltd. 1985. Geothermal mine air heating. Earth Phys.Br., Open File 85-24,106pp

Acres International Ltd. 1985. Moose Jaw geothermal study. Earth Phys.Br., Open File 85-7, 225pp

Allen, D.M. 1996. Steady-state and Transient Hydrologic, Thermal and Chemical Modelling of a Faulted Carbonate Aquifer used for Aquifer Thermal Energy Storage, Carleton University, Ottawa, Canada. PhD Thesis, Department of Earth sciences, Carleton University, Ottawa, Ontario, 642 pp.

Allen, D.M. Modelling protocol for successful simulations of flow and heat transport in ATES systems. Paper in Proceedings of the Stockton Geothermal Conference II, Stockton, N.J., March 16 & 17, 1997.

Allen, D. M. and Michel, F. A. 1997. Hydrologic and Thermal Simulations of an ATES System in Fractured Limestone, Carleton University, Canada. Paper in Proceedings of Megastock '97, 7th International Conference on Thermal Energy Storage, Sapporo, Japan, June 1997.

Allen, D.M., Ghomshei,M.M., Sadlier-Brown,.T.L., & two others. 2000. The current status of geothermal exploration and development in Canada. Proc.World Geothermal Congress, 2000.

Allen, D.M., Woo, C., Shymko, G.F. and Maynard, S. 2000. Operating strategies for ATES in areas with non-ideal climates. Paper in Proceedings of the 8th International Conference on Thermal Energy Storage, Terrastock. Stuttgart, Germany, August 27- Sept 3, 2000.

Allen, D.M. and Bridger, D.W. 2003. ATES Systems in Heterogeneous Aquifers: A Modelling Case Study. In Proceedings of the 9th International Conference on Thermal Energy Storage, Futurestock, Warsaw, Poland, September 1-4, 2003.

Allen, D.M. and Bridger, D.W. (2003). Dealing with load imbalances and aquifer heterogeneity: Design and monitoring of the ATES system in Agassiz, BC. In Proceedings of the Canadian Geotechnical Society - International Association of Hydrogeologists Joint Annual Conference, Winnipeg, Manitoba, September 29-October 1, 2003.

Allen, D.M., Grasby, S.E., and Voormeij, D.A. 2006. Determining the circulation depth of thermal springs in the southern Rocky Mountain Trench, southeastern British Columbia, Canada using geothermometry and borehole temperature logs. *Hydrogeology Journal* **14**, 159-172.

Anonymous 1981. The role of water in geothermal energy resources. In - Canada Water Year Book 1979-1980, Water Research Edition, Environment Canada, 104-105

Apex Airborne Surveys Ltd. 1982. Report on a helicopter E.M. and magnetometer survey in the Meager Creek area, British Columbia. Rept.to Nevin,Sadlier-Brown,Goodbrand,Ltd., 6pp+append.

B.C.Hydro,Power Authority 1982. Meager Creek mapping program - 1981. B.C.Hydro,Power Auth. Rept.SE8209, 23pp+append.

B.C.Hydro,Power Authority 1983. Meager Creek geothermal project summary report for 1982-83. B.C.Hydro,Power Auth., 36pp

Bawden,W.F. and Roegiers,J.C. 1980. Discussion and interpretation of the mathematics governing radial flow in a single horizontal rock fracture. Earth Phys.Br., Open File 80-5, 134pp

Bawden,W.F., Roegiers,J.-C. and Schlumberger,D. 1985. Gas escape from underground mined storage facilities - a multiphase flow phenomenon. Preprint

Beck,A.E. 1971. Prospects for geothermal power. Comments Earth Sci.Geophys.,1,139-149

Bens,A.R. and McCartan,J.J. 1982. Use of geothermal energy combined with conventional energy sources at the main campus University of Regina. Rept.to Univ.Regina, 137pp+diags.

Bens,A.R., McCartan,J.J. and Vigrass,L.W. 1982. Use of geothermal energy at the University of Regina - results of an engineering economic study. Proc. ENERGEX 82, Univ.Regina, Ed. Curtis,F.A.1123-1128

Bentkowski,W.H. and Lewis,T.J. 1983. Preliminary results of shallow drilling in the Garibaldi Volcanic Belt British Columbia,1982. Earth Phys.Br., Open File 83-23, 39pp

Bentkowski,W.H. and Lewis,T.J. 1984. Preliminary results from shallow drilling in the Alert Bay Volcanic Belt. Earth Phys.Br., Open File 84-2, 17pp

Bentkowski,W.H. and Lewis,T.J. 1985. Preliminary results from shallow drilling in the Anahim Volcanic Belt, B.C. Earth Phys.Br., Open File 85-9, 19pp

Bridger, D.W. and Allen, D.M. (in press, 2009). Heat Transport Simulations in a Heterogeneous Aquifer Used for Aquifer Thermal Energy Storage (ATES). Canadian Geotechnical Journal.

Bridger, D. W. and Allen, D.M. (2005). Designing aquifer thermal energy storage (ATES) systems. ASHRAE Journal, September, S32-S38.

Chorney,R.J. and Sherwood,R.L. 1981. Geothermal electric energy and its impacts on the environment. Dept.Environment,Env.Protn.Serv.,Pacif,Yukon Reg., Prog.Rept.81-05, 37pp

Clark,I.D. 1980. Isotope hydrogeology and geothermometry of the Mount Meager geothermal area. Thesis,M.Sc., University of Waterloo

Clark,I.D., Fritz,P. and Michel,F.A. 1980. Isotope hydrogeology and geothermometry of the Mount Meager geothermal area. Rept.to Geol.Surv.Can., 131pp

Clark,I.D., Fritz,P. and Souther,J.G. 1989. Geochemistry and isotope hydrogeology of the Mount Edziza - Mess Creek geothermal area. Can.J.Earth Sci., 26, 1160-1171

Clark,I.D., Fritz,P., Michel,F.A. and Souther,J.G. 1982. Isotope hydrogeology amd geothermometry of the Mount Meager geothermal area. Can.J.Earth Sci., 19, 1454-1473

Combs,J. 1979. Review of the proposed 1979 exploration program for the Meager Creek geothermal project. Rept.to B.C.Hydro and Power Auth.,14pp

Cousins,R.J. and Larkin,B.S. 1984. Low temperature geothermal energy in Canada. In - Energy Developments: New Forms, Renewables, Conservation, Ed.Curtis,F.A.,Proc.Energex Conf.,267-272

Crandall,J.T. and Sadlier-Brown,T.L. 1978. Data on geothermal areas - cordilleran Yukon, Northwest Territories, and adjacent British Columbia, Canada. Earth Phys.Br., Open File 78-1, 23pp+append+diagr.

D.R.Piteau and Assoc. 1985. Summerland Basin hydrogeological study. Earth Phys.Br., Open File 85-29, 82pp

Davis,E.E. and Lewis,T.J. 1984. Heat flow in a back-arc environment: Intermontane and Omineca Crystalline Belts, southern Canadian cordillera. Can.J.Earth Sci., 21, 715-726

Deep Grid Analysis Ltd. 1975. Deep resistivity surveys and supplementary geophysics at Meager Creek selected area, Pemberton, B.C. Rept.to Nevin Sadlier-Brown Goodbrand,Ltd., 15pp+append

Dragert,H., Law,L.K. and Sule,P.O. 1980. Magnetotelluric soundings across the Pemberton Volcanic Belt, British Columbia. Can.J.Earth Sci., 17, 161-167

Drury,M.J. 1983. Temperature gradients and heat production in two granitic batholiths of New Brunswick. Earth Phys.Br., Internal Rept. 83-9, 11pp

Drury,M.J. 1984. Assessment of the geothermal resources of Atlantic Canada. In - Energy Developments: New Forms, Renewables, Conservation, Ed.Curtis,F.A.,Proc.Energex Conf.,285-290

Elworthy,R.T. 1925. Hot springs in western Canada; their radioactive and chemical properties. Min.Br.Invest.Miner.Resour.Min.Indust., 1-33

Epstein,N., Watkinson,A.P. and Yu,W. 1986. A study of the fouling characteristics of prairie geothermal waters. Dept.Chem.Engng., Univ.Brit.Columbia, Rept.to Nat.Res.Council, OST-83-00414,11pp+tables+append

Everdingen,R.O.van. 1972. Thermal and mineral springs in the southern Rocky Mountains of Canada. Environment Canada, 151pp.

Fairbank Engineering LTd. 1992. Geothermal feasibility study for the use of hot water near Riondel. B.C. Geol.Surv.Can., Open File 2502, 108 pp

Fairbank,B.D. and twelve others 1992. Geothermal resources of British Columbia. Geol.Surv.Can., Open File 2526.

Fairbank,B.D., Openshaw,R.E., Souther,J.G. and Stauder,J.J. 1981. Meager Creek geothermal project - an exploration case history. In - Geothermal Potential of the Cascade Mountain Range, Exploration and Development, Spec.Rept.10,Geothermal Resources Coun.,15-19

Fairbank,B.D., Reader,J.F. and Sadlier-Brown,T.L. 1980. Report on 1979 drilling and exploration program Meager Creek geothermal area upper Lillooet River, British Columbia. Rept.to B.C.Hydro and Power Authority,.57pp+append.

Fairbank,B.D., Shore,G.A., Werner,L.J. and Nevin,A.E. 1979. Report on 1978 field work Meager Creek geothermal area upper Lillooet River, British Columbia. Earth Phys.Br., Open File 79-10, 82pp+append.

Fritz,P., Clark,I.D., Michel,F.A. and Souther,J.G. 1980. Isotope hydrology and geothermometry of the Mount Meager geothermal area. Trans.Geothermal Resour.Coun., 4, 161-164.

Garven,G. and Vigrass,L.W. 1985. Modelling of deep groundwater flow in Saskatchewan. Earth Phys.Br., Open File 85-17, 36pp+24maps

Geoprobe Ltd. 1978. Report on the Maxi-probe EMR-16 test survey around Meager Creek area (B.C.). Rept.to Geol.Surv.Can., 12pp+append.

Ghomshei,M.M., Croft,S.A.S. and Stauder,J.J. 1986. Geochemical evidence of chemical equilibria in the south Meager Creek geothermal system, British Columbia, Canada. Geothermics, 15, 49-61

Ghomshei,M.M., MacLeod,K., Sadlier-Brown,T.L., Meech,J.A. and Dakin,R.A. 2005. Canadian geothermal energy poised for takeoff. Proc. World Geothermal Congress 2005.

Glass,I.I. 1976. Utilization of geothermal energy. Univ.Toronto, Inst.Aerospace Studies, Review 40, 21pp

Glass,I.I. 1977. Prospects for geothermal energy applications and utilization in Canada. Energy, 2, 407-428

Gorrell,H.A. 1978. Hot water under the plains. Geos, Energy Mines and Resources, Ottawa, Spring, 12-14

Gorrell,H.A. 1979. Geothermal studies in the plains region of western Canada. Bull.Can Inst.Min.Metall., 72, Oct., 66-69

Gorrell,H.A. 1984. Application of existing data to low temperature geothermal exploration. In - Energy Developments: New Forms, Renewables, Conservation, Ed.Curtis,F.A., Proc.Energex Conf.,291-295

Grant,M.B. and Michel,F.A. 1985. Study of the hydrogeology of the White Lake Basin, British Columbia. Earth Phys.Br., Open File 85-28, 63pp

Grasby, S.E., Allen, C.C., Longazo, T.G., Lisle, J.T., Griffin, D.W., and Beauchamp, B. (2003) Supra-glacial sulphur springs and associated biological activity in the Canadian High Arctic – Signs of life beneath the ice. *Astrobiology*, 3, 583-596.

Grasby, S.E., van Everdingen, R.O., Bednarski, J., and Lepitzki, D.A.W. (2003) Travertine mounds of the Cave and Basin National Historic Site, Banff National Park. *Canadian Journal of Earth Sciences*, 40, 1501-1513.

Grasby, S.E., Majorowicz, J.A., Ko, M. (2009) Geothermal maps of Canada. Geological Survey of Canada, Open File 6167, 2009; 35 pages

Grasby, S.E. and Lepitzki, D.A.W. (2002) Physical and chemical properties of the Sulphur Mountain thermal springs, Banff National Park, and implications for endangered snails. *Canadian Journal of Earth Sciences,* 39, 1349-1361.

Grasby, S.E., and Hutcheon, I. (2001) Controls on the distribution of thermal springs in southern Alberta and British Columbia. *Canadian Journal of Earth Sciences*, 38, 427-440.

Grasby, S.E., Hutcheon, I., and Krouse, H.R. (2000) The influence of water/rock interaction the chemistry of thermal springs in western Canada. *Applied Geochemistry*, 15, 439-454.

Haines,P.J. and Jessop,A.M. 1975. Geothermal potential and geothermal exploration in the Caribbean Islands. Canadian International Development Agency, 30pp

Hammerstrom,L.T. and Brown,T.H. 1977. Geochemistry of thermal waters in the Mount Meager Hotsprings area, British Columbia. Geol.Surv.Can., Paper 77-1a, 283-285

Hammerstrom,L.T. and Brown,T.H. 1977. The geochemistry of thermal waters from the Mount Meager Hotsprings area, B.C. Geol.Surv.Can., Open File 532, 32pp+append.

Hutchence,K. and Vigrass,L.W. 1985. Subsurface modelling for geothermal production and energy storage. Earth Phys.Br., Open File 85-16, 57pp

Hutchence,K., Law,A.G., Vigrass,L.W. and Weston,J.H. 1984. Geothermal aquifer modelling: a low temperature production/disposal system. Proc.Fourth Int.Conf.Math.Modelling In Science and Technology, Zurich, Switzerland, Pergamon Press, 634-639

Hutchence,K., Law,A.G., Weston,J.H. and Vigrass,L.W. 1984. Predicting thermal breakthrough for a liquid phase geothermal system. Appl.Math.Notes, 9, 13-19

Hutchence,K., Vigrass,L.W., Law,A.G. and Weston,J.H. 1984. Modelling of the Regina geothermal aquifer. In - Energy Developments: New Forms, Renewables, Conservation, Ed.Curtis,F.A.,Proc.Energex Conf.,309-313

Hutchence,K., Weston,J.H., Law,A.G. and Vigrass,L.W. 1986. Modeling of a liquid phase geothermal doublet system at Regina, Saskatchewan, Canada. Wat.Resour.Res., 22, 10, 1469-1479

Ingham,M.R., Bingham,D.K. and Gough,D.I. 1983. A magnetovariational study of a geothermal anomaly. Geophys.J.R.Astr.Soc., 72, 597-618

Jaques, Whitford & Associates Ltd. 1987. Town of Springhill geothermal demonstration project: report on the test drilling and pumping test results. Rept to Town of Springhill Geothermal Committee, 33pp+ append.

Jessop,A.M. 1975. Energy R and D Program statement - Task 5 - Exploit renewable energy resources - Program 4 - Geothermal energy. Earth Phys.Br., Geothermal Ser.4, 6pp

Jessop,A.M. 1975. Geothermal energy. Geos, Energy Mines and Resources, Ottawa, Spring, 2-4

Jessop,A.M. 1976. Geothermal energy from sedimentary basins. Earth Phys.Br., Geothermal Ser.8, 10pp

Jessop,A.M. 1977. The role of non-conventional energy resources - geothermal. In - The Canadian Energy Situation in 1990 and Beyond, Proc.Can.Natnl. Energy Forum

Jessop,A.M. 1978. Geothermal energy from sedimentary formations of western Canada. In - Geothermal Energy, a Novelty Becomes a Resource, Trans.Geothermal Resour. Coun., 2, 331-334

Jessop,A.M. 1982. Using the heat of the earth. Land, Environment Canada, 3, 2, 10-12

Jessop,A.M. 1984. Geothermal energy in Canada - a review of the resources. In - Energy Developments: New Forms, Renewables, Conservation, Ed.Curtis,F.A.,Proc.Energex Conf., 263-266

Jessop,A.M. 1985. Geothermal energy in Canada. Trans.Geothermal Resour.Coun., 9, 37-42.

Jessop,A.M. 1988. Geothermal regimes and geothermal resources of sedimentary basins. In - hydrogeology of sedimentary basins: application to exploration and exploitation, Third Can/Am.Conf.Hydrogeol.Natl.Water Well Assoc. (US), 127-139

Jessop,A.M. 1998. Geothermal energy in Canada. Geoscience Canada, 25, 1, 1998.

Jessop,A.M. and Church,B.N. 1991. Geothermal drilling in the Summerland Basin, British Columbia, 1990. Geol.Surv.Can., Open File 2348, 19 pp.

Jessop,A.M. and Vigrass,L.W. 1984. The Regina geothermal experiment - thermal aspects. In - Energy Developments: New Forms, Renewables, Conservation, Ed.Curtis,F.A., Proc. Energex Conf., 315-318

Jessop,A.M. and Vigrass,L.W. 1989. Geothermal measurments in a deep well at Regina, Saskatchewan. J.Volcan.Geothermal Res., 37, 151-166

Jessop,A.M., Ghomshei,M.M. and Drury,M.J. 1991. Geothermal energy in Canada. Geothermics, 20, 369-385.

Jessop,A.M., MacDonald,J.K. and Spence,H. 1995. Clean energy from abandoned mines at Springhill, Nova Scotia. Energy Sources, 17, 93-106

Jessop,A.M., and nine others. 2005. The Canadian geothermal data compilation. Geol.Surv.Can., Open File 4887, one CD.

John A.Leslie and Assoc.Ltd. 1981. Investigation of geothermal energy resources - Nova Scotia and Prince Edward Island. Earth Phys.Br., Open File 81-9, 120pp

John A.Leslie and Assoc.Ltd. 1982. Investigation of geothermal energy resources, Atlantic Provinces. Earth Phys.Br., Open File 82-8, 127pp+map

John A.Leslie and Assoc.Ltd. 1983. Geothermal gradients in granite batholiths of New Brunswick. Earth Phys.Br., Open File 83-19, 90pp

John A.Leslie and Assoc.Ltd. 1983. Investigation of geothermal energy resources - Atlantic Provinces. Earth Phys.Br., Open File 83-20, 37pp

John A.Leslie and Assoc.Ltd. 1984. Geothermal investigation: Prince Edward Island drilling. Earth Phys.Br., Open File 84-3, 60pp

John A.Leslie and Assoc.Ltd. 1984. Investigation of geothermal energy resources: Atlantic Canada. Earth Phys.Br., Open File 84-5, 44pp and 1 map

John A.Leslie and Assoc.Ltd. 1985 1984 investigations of geothermal energy resoucres, Atlantic provinces. Earth Phys.Br., Open File 85-8, 69pp

John A.Leslie and Assoc.Ltd. 1985. Geothermal investigation, Prince Edward Island drilling, MacDougall, Prince County, hole number EPB 345. Earth Phys.Br., Open File 85-10, 78pp

John M. Booth Engineering Ltd 1985. Outline report on the minewater geothermal heat source. Unpublished report to Earth Physics Branch

Johnstone,M.C. 1982. Study of the feasibility of using Middle Devonian formation water from the Clarke Lake Gas Field, N.E. British Columbia, as a geothermal energy resource. Unpublished Memorandum to Petr.Resources Branch, BC Min.Energy, Mines Petr. Resources.

Jones,F.W. and Majorowicz,J.A. 1985. Study of existing temperature data from Canadian sedimentary basins - phase 4. Earth Phys.Br., Open File 85-6, 79pp

Jones,F.W., Kushigbor,C., Lam,H.L., Mahorowicz, J.A., et al 1984. Estimates of terrestrial thermal gradients and heat flow variations with depth in the Hinton-Edson area of the AlbertaBasin derived from petroleum bottom-hole temperature data. Geophys. Prospecting, 32, 1111-1130

Jones,F.W., Lam,H.L. and Majorowicz,J.A. 1985. Temperature distributions at the Paleozoic and Precambrian surfaces and their implications for geothermal energy recovery in Alberta. Can.J.Earth Sci., 22, 1774-1780

Jones,F.W., Lam,H.L. and Yuen,D. 1982. A study of existing temperature data from Canadian sedimentary basins. Earth Phys.Br., Open File 82-22, 107pp

Jones,F.W., Majorowicz,J.A. and Lam,H.L. 1983. A study of existing temperature data from Canadian sedimentary basins, phase 2. Rept.to Earth Phys.Br.

Jones,F.W., Majorowicz,J.A. and Lam,H.L. 1984. A study of existing temperature data from Canadian sedimentary basins, phase 3. Rept.to Earth Phys.Br., 161pp

Jones,F.W., Rahman,M., Lam,H.L. and Sworder,J.E. 1983. A preparatory study for application of geothermal energy in the Hinton/Edson area of Alberta. Rept. to Min.Energy & Natural Resources, Alberta, 177pp + append.

Jones,F.W., Rahman,M., Majorowicz,J.A. and Lam,H.L. 1983. A study of thermal properties of sedimentary rocks of western Canada. Earth Phys.Br., Open File 83-7, 1079pp

K.R.T.A.Ltd. 1982. Geothermal project Meager Creek well completion report MC-1. Rept.to B.C. Hydro,Power Auth., 56pp

K.R.T.A.Ltd. 1982. Geothermal project Meager Creek well completion report MC-2. Rept.to B.C.Hydro and Power Auth., 63pp

K.R.T.A.Ltd. 1982. Review of geochemical data from the Meager Creek geothermal area. Rept.to B.C.Hydro and Power Auth., 32pp

K.R.T.A.Ltd. 1983. Geothermal project Meager Creek well completion report MC-3. Rept.to B.C.Hydro and Power Auth., 70pp

K.R.T.A.Ltd. 1983. Geothermal project Meager Creek, summary report for 1981-82. Rept.to B.C.Hydro and Power Auth., 14pp+append.

K.R.T.A.Ltd. 1983. Report on Meager Creek geothermal project 1981-1982. Rept.to B.C.Hydro and Power Auth., 214pp+append.

Kamp,G.van der. 1984. Evaluating the influence of groundwater flow systems on geothermal conditions. In - Energy Developments: New Forms, Renewables, Conservation, Ed.Curtis,F.A.,Proc.Energex Conf.,297-301

Katherine Arkay Consulting 1992. Geothermal energy from abandoned mines: a methodology for an inventory, and inventory data for abandoned mines in Quebec and Nova Scotia. Geol.Surv.Can., Open File 3825

Katherine Arkay Consulting 1993. First Springhill Geothermal Energy Conference, Springhill, Nova Scotia, summary report. Geol.Surv.Can., Open File 2773, 60pp + append.

Lam,H.L. and Jones,F.W. 1984. An assessment of the low-grade geothermal potential in a foothills area of west-central Alberta. In - Energy Developments: New Forms, Renewables, Conservation, Ed.Curtis,F.A.,Proc.Energex Conf.,273-278

Lam,H.L. and Jones.F.W. 1985. Geothermal energy potential in the Hinton-Edson area of west-central Alberta. Can.J.Earth Sci., 22, 369-383

Lam,H.L., Jones,F.W. and Lambert,C. 1982. Geothermal gradients in the Hinton area of west-central Alberta. Can.J.Earth Sci., 19, 755-766

Lambert,C. 1980. Report on geothermal gradient study of two areas of Alberta. Inst. Earth, Planet Phys.,Univ.Alberta, 21pp+figs.

Lefebvre,T.H.(chairman). 1981. Geothermal energy. In - Energy Alternatives, Report of Special Committee on Alternative Energy and Oil Substitution to the Parliament of Canada, 171-177

Legg,J.F. 1988. The record and status of geothermal energy R&D in Canada from the perspective of the Government of Canada. Energy, Mines and Resources, Office of Energy Research and Development,3399 + appendices

Leroux,J. 1980. Geothermal potential of the Coryell Intrusions, Granby River area, British Columbia. Geol.Surv.Can., Paper 80-1b, 213-215

Lewis,J.F. 1978. Preliminary field report of drilling near Mt. Meager and Mt.Cayley volcanic centres - 1977. Earth Phys.Br., Open File 78-2, 12pp+append+diagr.

Lewis,J.F. and Jessop,A.M. 1981. Heat flow in the Garibaldi Volcanic Belt, a possible Canadian geothermal resource area. Can.J.Earth Sci., 18, 366-375

Lewis,T.J. 1982. Geothermal gradients on the west side of Okanagan Lake, B.C. Earth Phys.Br., Open File 82-06, 59 pp.

Lewis,T.J. 1984. Geothermal energy from Penticton Tertiary Outlier, British Columbia. Can.J.Earth Sci., 21, 181-188

Lewis,T.J. and Souther,J.G. 1978. Meager mountain, B.C. - a possible geothermal energy resource. Earth Phys.Br., Geothermal Ser.9, 17pp

Lewis,T.J. and Werner,L. 1982. Geothermal gradients on the west side of Okanagan Lake, B.C. Earth Phys.Br., Open File 82-6, 58pp

Lewis,T.J., Allen,V.S., Taylor,A.E. and Jessop,A.M. 1979. Temperature observations during drilling of two 400 m wells in the Coryell intrusives north of Grand Forks, British Columbia. Earth Phys.Br., Open File 79-2,16pp+diagr.

Lewis,T.J., Judge,A.S. and Souther,J.G. 1978. Possible geothermal resources in the Coast Plutonic Complex of southern British Columbia, Canada. Pure Appl. Geophys., 117, 172-179

Loveseth,G.E. 1989. The geothermal resources of Saskatchewan and S.W. Manitoba. Geol.Surv.Can., Open File 2422, 19 pp.

Loveseth,G.E. and Pfeffer,B.J. 1988. Location, indentification and inventory of aquifers with the greatest geothermal potential in the sedimentary rocks of Alberta. Geol.Surv.Can., Open File 2423, 28 pp.

Majorowicz, J.A., and Moore M.C. 2008 Enhanced Geothermal Systems (EGS) Potential in the Alberta Basin. ISEEE, UofC, ISEEE Open File Report, 34p, http://www.ucalgary.ca/~wenet/Geothermal%20Report/ISEEE%20Research%20Report_Moore-geothermal.pdf

Majorowicz, J. and Grasby, S.E**.** 2010 Heat flow, depth-temperature variations and stored thermal energy for enhanced geothermal systems in Canada. Journal of Geophysics and Engineering, 7, 232-241.

Majorowicz, J. and Grasby, S.E. 2010 High potential regions for enhanced geothermal systems in Canada. Natural Resources Research. 19, 177-188

Majorowicz,J.A., Jones,F.W. and Jessop,A.M. 1986. Geothermics of the Williston Basin in Canada in relation to hydrodynamics and hydrocarbon occurrences. Geophysics, 51, 3, 767-779

Majorowicz,J.A., Jones,F.W. and Lam,H.L. 1984. A comment on "a magnetovariational study of a geotheral anomaly" by M.R.Ingham, D.K.Bingham and D.I,Gough. Geophys. J.R. Astr. Soc., 76, 667-672

Majorowicz,J.A., Jones,F.W., Lam,H.L. and Jessop,A.M. 1984. Heat flow and geothermal gradient studies in the Alberta Basin, an essential part of geothermal potential evaluation. In - Energy Developments: New Forms, Renewables, Conservation, Ed.Curtis,F.A., Proc.Energex Conf.,279-284

Majorowicz,J.A., Jones,F.W., Lam,H.L. and Jessop,A.M. 1984. The variability of heat flow both regional and with depth in southern Alberta, Canada - effect of groundwater flow. Tectonophysics, 106, 1-29

Majorowicz,J.A., Jones,F.W., Lam,H.L. and Jessop,A.M. 1985. Heat flow and geothermal gradient studies in the Alberta Basin, an essential part of geothermal potential evaluation. Proc.Energex Conf., 279-284

Majorowicz,J.A., Jones,F.W., Lam,H.L. and Jessop,A.M. 1985. Regional variations of heat flow differences with depth in Alberta, Canada. Geophys.J.R.Astr.Soc., 81, 479-487

Majorowicz,J.A., Jones,F.W., Lam,H.L. and Jessop,A.M. 1985. Terrestrial heat flow and geothermal gradients in relation to hydrodynamics in the Alberta Basin, Canada. J.Geodyn., 4, 265-283

Majorowicz,J.A., Jones,F.W., Lam,L. and Linville,A. 1985. Topography and the subsurface temperature regime in the western Canadian sedimentary basin: implications for low-enthalpy geothermal energy recovery. Geothermics, 14, 175-187

Majorowicz, J., Grasby, S.E., and Skinner, W. (2009) Estimation of shallow geothermal energy resources in Canada – Heat gain and sink. Natural Resources Research. 18 (2), 95-108; DOI:10.1007/s11053-009-9090-4, Springer

Mark,D.G. 1978. Seismic refraction study in the Meager Mountain geothermal region, Lillooet River Valley, B.C. Earth Phys.Br., Open File 78-3(part), 11pp+diagr.

Mark,D.G. 1978. Seismic refraction study in the Meager mountain geothermal region, Job Creek area, upper Lillooet River Valley, B.C. Earth Phys.Br., Open File 78-3(part), 11pp+diagr.

McDonald,J., Pollock,D. and McDermot,B. 1978. Hotsprings of western Canada - a complete guide. Labrador Tea Co., 161pp.

McLellan,J.D., Hasegawa,H.H., Roegiers,J.G. and Jessop,A.M., 1987. Hydraulic fracturing experiment at the University of Regina campus. Can.Geotech.J. ,23, 548-555.

Michel,F. and Fritz,P. 1979. Isotope hydrology of the Meager Creek thermal waters. Rept. to Geol.Surv.Can.,10pp+append.

Michel,F. and Fritz,P. 1980. Isotope hydrology of the Meager Creek geothermal waters. Rept.to Geol.Surv. Can.,24pp

Michel,F.A. and Fritz,P. 1985. An initial study of the hydrology of White Lake Basin, B.C. Earth Phys.Br., Open File 85-27, 37pp

Michel, F.A. and Allen, D.M. 1997. Optimizing Well Configurations for Aquifer Thermal Energy Storage Systems. Paper in Proceedings of Megastock '97, 7th International Conference on Thermal Energy Storage, Sapporo, Japan, June 1997.

Michel, F.A. and Allen, D.M. 2000. ATES well field study and the choice of aquifer in a sedimentary environment: A case study. Paper in Proceedings of the 8th International Conference on Thermal Energy Storage, Terrastock. Stuttgart, Germany, August 27- Sept 3, 2000.

Michel, F.A. and Allen, D.M. 2003. Identification and management of potential problems in aquifer thermal energy storage systems. In Proceedings of Canadian Geotechnical Society - International Association of Hydrogeologists Joint Annual Conference, Winnipeg, Manitoba, September 29-October 4, 2003.

Moore,J.N., Adams,M.C. and Stauder,J.J. 1983. Geochemistry of the Meager Creek geothermal field, British Columbia, Canada. Trans.Geothermal Resour.Coun., 7, 315-319

Morofsky.E. 1982. Aquifer thermal energy storage at the Scarborough Government of Canada building. In - A forum on Energy Self-reliance: Conservation, Production and Consumption. Ed.Curtis,F.A., Proc. Energex Conf., 1119-1122

Nevin,A.E. and Sadlier-Brown,T.L. 1972. Electricity from geothermal steam and possible utilization in British Columbia. Western Miner, April, 88-93

Nevin,A.E. and Stauder,J. 1975. Canada - early stages of geothermal investigation in British Columbia. Proc.U.N.Symp.Geothermal Res., San Francisco, 1161-1165

Nevin,A.E., Crandall,J.T., Souther,J.G. and Stauder,J. 1978. Meager Creek geothermal system, British Columbia, part 1 - Exploration and research programme. In - Geothermal Energy, a Novelty Becomes a Resource, Trans.Geothermal Resour.Coun.,2,491-494

Nevin,Sadlier-Brown,Goodbrand Ltd. 1977. Report on 1976 geothermal investigation at Meager Creek - north and northeast flanks of the volcanic complex. Rept.to B.C.Hydro and Power Authority,.0pp+append.

Nevin,Sadlier-Brown,Goodbrand Ltd. 1978. Progress report for 1977 Meager Creek geothermal project investigations for 1977-1978. Rept.to B.C.Hydro and Power Authority,. 15pp+append.

Nevin,Sadlier-Brown,Goodbrand Ltd. 1978. Report on 1977 geothermal investigation at Meager Creek principally on the northeast flank of the volcanic complex. Rept.to B.C.Hydro and Power Authority,.22pp+append

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1974. Investigation of geothermal resources in southwestern British Columbia. Rept.to B.C.Hydro and Power Authority,. 40pp+diagr+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1975. Detailed geothermal investigation at Meager Creek. Rept.to B.C.Hydro and Power Authority,.18pp+diagr+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1975. Interim report on Meager Creek selected area geothermal investigations phase 2. Rept.to B.C.Hydro and Power Auth.,17pp+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1975. Preliminary investigation of the geothermal resources of western Vancouver Island. Rept.to B.C.Hydro and Power Authority, 10pp+diagr+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1977 1976 geothermal investigation at Meager Creek. Rept.to B.C.Hydro and Power Authority,.18pp+diagr+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1980. Report on 1979 drilling and exploration program Meager Creek geothermal area upper Lillooet River, British Columbia. Rept.to B.C. Hydro and Power Auth.,.57pp+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1981. Geothermal energy resources in British Columbia. Rept.to Min.Energy,Mines,Petr.Resources, 142pp+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1981. Meager Creek geothermal area MC-1 geological summary, July 1981 - October 1981. Rept.to B.C.Hydro and Power Auth.,10pp+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1981. Meager Creek geothermal area slim hole drilling summary, volume 1: south reservoir area. Rept. to B.C.Hydro,Power Auth.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1981. Meager Creek geothermal area slim hole drilling summary, volume 2: Lillooet River valley. Rept.to B.C.Hydro and Power Auth.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1981. Report on 1980 drilling and exploration program Meager Creek geothermal area, upper Lillooet River, British Columbia. Rept. to B.C. Hydro,Power Auth.,.123pp+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1982. Interpretation of an airborne electromagnetic survey over the Meager Creek geothermal area. Rept. to Geol.Surv.Canada, 30pp

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1982. Report on 1981 drilling and exploration program Meager Creek geothermal area upper Lillooet River, British Columbia. Rept.to B.C. Hydro and Power Auth., 93pp+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1982. Report on geothermal reconnaissance exploration of selected areas in southwestern British Columbia. Rept.to B.C.Hydro and Power Auth., 102pp+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1983. Report on 1982 geological mapping program, north reservoir area, Meager Creek, B.C. Rept.to B.C.Hydro and Power Auth.,14pp+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1983. Report on 1982 temperature gradient drilling on Shovelnose Creek at Mount Cayley, southwestern British Columbia. Rept.to Geol. Surv. Can., 12pp+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1983. Report on a reconnaissance hydrogeochemistry survey of the south- western drainage of Mount Cayley, British Columbia. Rept.to Geol.Surv.Can., 17pp+append.

Nevin,Sadlier-Brown,Goodbrand,Ltd. 1984. Report on preliminary evaluations of three potential geothermal sites in southern British Columbia. Rept. to Geol.Surv.Canada, 11pp + append.

Noel,G.A. 1978. Cenozoic rocks in the western Canadian cordillera of British Columbia. Geol.Surv.Can., Open File 659, 39pp

Nolan, Davis & Associates Ltd 1984. Groundwater flow patterns in Carboniferous sediments of Atlantic Canada. Earth Phys.Br., Open File 84-29, 101pp and 1 map

Openshaw,R.E., Britton,J.M., Fairbank,B.D. and Reader,J.F. 1982. Report on 1981 drilling and exploration program, Meager Creek geothermal area upper Lillooet River, British Columbia. Rept.to B.C.Hydro and Power Auth., 93pp+append.

Pham van Ngoc. 1976. Magneto-telluric reconnaissance survey in the Lillooet Valley, British Columbia. Earth Phys.Br., Open File 77-20, 22pp+diagr.

Pham van Ngoc. 1978. Magneto-telluric prospecting in the Mount Meager geothermal region (British Columbia). Earth Phys.Br., Open File 78-6e(engl.), 78-6f(fre.), 31pp+diagr.

Pham van gnoc 1980. Etude magneto - tellurique de la region du Mont Meager et de la Vallee de Squamish, Colombie Britannique. magneto-telluric survey of the Mount Meager region of the Squamish Valley (British Columbia). Earth Phys.Br., Open File 80-8(French) 80-8-E(English), 77pp

Phoenix Geophysics Ltd. 1982. Magnetotelluric survey data North Thompson Valley area British Columbia. Rept.to Geol.Surv.Can., 3pp+append.

Phoenix geophysics Ltd. 1984. Magnetotelluric survey data, Mount Cayley area, British Columbia. Geol.Surv.Can., Open File 1018

Piteau and Assoc. 1984. Summerland Basin hydrogeological study. Earth Phys.Br., Open File 84- , 49pp+append.

Piteau and Assoc. 1988. Geochemistry and isotope hydrogeology of the Mount Edziza and Mess Creek geothermal waters. Geol.Surv.Can., Open File 1732, 47pp.

Postlethwaite,J., Gummadi,V., Scoular,J.R. and Vigrass,L.W. 1980. Corrosion testing on western Canada geothermal waters. Univ.Regina,Rept.to Public Works Can., 8pp

Postlethwaite,J., Vigrass,L.W., Gummadi,V. Neufeld,R. and Kybett,B.D. 1980. Water chemistry testing on western Canada geothermal waters. Univ.Regina,Rept.to Public Works Can., 12pp+append

Rahman,M., Jones,F.W., Lam,H.L. and Hutchence,K. 1984. Temperature front progression associated with a geothermal well doublet: a numerical study. Geothermics, 13, 319-331

Read,P.B. 1977. Meager Creek Volcanic Complex, southwestern British Columbia. Geol.Surv.Can., Paper 77-1a, 277-281

Reader,J.F. and Croft,S.A.S. 1984 1982 temperature gradient drilling on Shovelnose Creek at Mount Cayley, southwestern British Columbia. Geol.Surv.Can., Open File 1017

Reader,J.F. and Fairbank,B.D. 1983. Heat flow in the vicinity of the Meager Volcanic Complex, southwestern British Columbia. Trans.Geothermal Resour.Coun., 7, 535-539

Reid, Crowther and Partners Ltd. 1979. Environmental reconnaissance report Meager Creek geothermal area. Rept.to B.C.Hydro and Power Authority,.131pp+append.

Reid, Crowther and Partners Ltd. 1980. Geothermal energy utilisation in N.E. British Columbia: a direct heat application, Phase 1. Unpublished report to BC Min.Energy, Mines Petr. Resources, Energy Conservation and Technology.Div.

Reid, Crowther and Partners,Ltd. 1980. Meager mountain geothermal project status of environmental studies baseline data collection program. Rept.to B.C.Hydro and Power Authority,.77pp+append.

Roegiers,J.C. and McLennan,J.D. 1978. Numerical modelling of pressurized fractures. Rept.to Los Alamos Sci.Lab. 225pp

Roegiers,J.C. and McLennan,J.D. 1980. Stress determination at great depth of the geothermal well on the University of Regina campus. Earth Phys.Br., Open File 80-7, 110pp

Roegiers,J.C. and Wiles,T.D. 1981. Hydraulic fracturing of rock masses. Earth Phys.Br., Open File 81-10, 31pp

Roegiers,J.C., Curran,J.H. and Bawden,W.F. 1979. Numerical modelling of flow in fractured rock masses - discontinuous versus continuum approaches. Earth Phys.Br., Open File 79-8, 119pp

SNC group 1982. Survey of geothermal heat extraction technology. Rept. to Nat.Res.Council Ottawa, 192pp

Scintrex Ltd. 1981. Report on magnetometric resistivity (MMR) survey Meager Mountain geothermal resource British Columbia. Rept.to Geol.Surv. Can.,9pp+figs

Shore,G.A. 1978. Meager Creek geothermal system, British Columbia, part 3 - Resistivity methods and results. In - Geothermal Energy, a Novelty Becomes a Resource, Trans.Geothermal Resour.Coun.,2,593-596

Shore,G.A. 1981. Report on a resistivity survey in the vicinity of Mt. Cayley, august 1980. Geol.Surv.Can., Open File 792

Shore,G.A. 1983. Application and interpretation of multiple pole-pole resistivity survey, Mt. Cayley, B.C. Trans.Geothermal Resour.Coun., 7, 545-550

Shore,G.A. 1983. Electrical resistivity results from the Anahim Volcanic Belt, B.C. Trans.Geothermal Resour.Coun., 7, 551-554

Shore,G.A. 1984. Report on E-Scan multiple pole resistivity survey at Mt. Cayley, British Columbia. Geol.Surv.Can., Open File 1019, 12pp+append

Shore,G.A. and Ryder,A.J.D. 1986. Mapping the Makushin Reservoir with 3-D E-scan resistivity. Trans.Geothermal Resour.Coun.,10,229-236

Shore,G.A. and Schlax,M.G. 1982. Report on coordination and review of resistivity survey results from the Meager Creek geothermal area, 1974 to present. Rept.to B.C.Hydro and Power Auth., 68pp+append.

Souther,J.G. 1975. Geothermal potential of western Canada. Proc.U.N.Symp.Geothermal Res., San Francisco, 259-267

Souther,J.G. 1976. Geothermal power, the Canadian potential. Geoscience Canada, 3, 14-20

Souther,J.G. 1979. Canadian Geothermal Research Program. Am.Inst/Petrol.Geol., 391-400,

Souther,J.G. 1980. Geothermal reconnaissance in the central Garibaldi Belt, British Columbia. Geol.Surv.Can., Paper 80-1a, 1-11

Souther,J.G. 1981. Projected geothermal energy development in Canada. Proc.Epri Natl.Mtg., 7.51-7.56,Approx

Souther,J.G. 1991. Geothermal Energy. In - Energy and groundwater resources of the Canadadian Cordillera, Geology of the Cordilleran Orogan in Canada, Ed Gabrielse,H. and Yorath,C.J. Geol.Surv.Can., Geology of Canada, No.4, 787-792.

Souther,J.G. and Dellechaie,F. 1984. Geothermal exploration at Mt. Cayley - a Quaternary volcano in southwestern British Columbia. Trans.Geothermal Resour.Coun., 8, 463-468

Souther,J.G. and Halstead,E.C. 1969. Mineral and thermal waters of Canada. 23rd.Int.Geol.Cong., Prague, 225-256

Souther,J.G. and Halstead,E.C. 1973. Mineral and thermal waters of Canada. Geol.Surv.Can., Paper 73-18, 32pp

Sproule Associates Ltd. 1976. Report on study of geothermal resources in western Canadian sedimentary basins from existing data, phase one. Earth Phys.Br., Open File 77-13, 110pp+diagr.

Sproule Associates Ltd. 1977. Report on study of geothermal resources in western Canadian sedimentary basins from existing data, phase two. Earth Phys.Br., Open File 77-14, 127pp+diagr.

Sproule Associates Ltd. 1983. Report on study of the feasibility of geothermal reservoir mapping in deep sedimentary basins using existing data. Earth Phys.Br., Open File 83-27, 80pp+maps

Sproule Associates Ltd. and Angus-Butler-Engng,1980,Ltd. 1981. Report on preliminary assessment of the potential applications of geothermal energy. Earth Phys.Br., Open File 81-7, 86pp

Stauder,J.J. 1980. Meager Creek geothermal prospect,British Columbia 1979 progress report. Proc EPRI Natl.Mtg., 4.36-4.43, Approx

Thomas,M.D. and Willis,C. 1989. Gravity modelling of the Saint George Batholith and adjacent terrain within the Appalachian Orogen, southern New Brunswick. Can.J.Earth Sci., 26, 561-576

UMA Engineering Ltd. 1985. Feasibility study in the use of geothermal energy to heat large facilities. Earth Phys.Br., Open File 85-25, 165pp

Univ.Utah,Res.Inst. 1983. Multielement geochemistry of the Meager Creek geothermal system. Rept.to Nevin,Sadlier-Brown,Goodbrand,Ltd., 25pp+append.,Approx

Vandenberghe,D.G. and Vigrass,L.W. 1979. Low-grade geothermal energy - feasibility and demonstration at Regina, Canada. Proc.Intern.Conf.Alt.Energy Sources, Miami

Vaughan Engineering Associates Ltd. 1992. Feasibility study to establish a community heating system in the Town of Springhill, N.S. using warm mine water. Unpublished report to CANMET

Vigrass,L.W. 1979. Final well report, U of R Regina 3-8-17-19 (W.2nd.Mer.) Saskatchewan. Earth Phys.Br., Open File 79-9, 36pp+diagr.

Vigrass,L.W. 1979. Utilization of low-grade geothermal energy. Proc.Conf.Energy Commun.Planning,Prairies

Vigrass,L.W. 1980. Completion and pump test, U. of Regina 3-8-17-19, phase 1b - geothermal project. Earth Phys.Br., Open File 80-6, 90pp

Vigrass,L.W. 1982. Geothermal energy from the Williston sedimentary Basin at Regina Canada. Proc.Int.Conf.Geothermal Energy, Florence, Italy, 113-122

Vigrass,L.W. 1983. University of Regina Geothermal Project phase IIa: Work preliminary to drilling of disposal well and building of pipeline. Unpublished report to Earth Physics Branch.

Vigrass,L.W. and Jessop,A.M. 1984. Regina geothermal experiment - geological and hydrological aspects. In - Energy Developments: New Forms, Renewables, Conservation, Ed.Curtis,F.A.,Proc.Energex Conf.,303-308

Vigrass,L.W., Bens,A.R., McCartan,J.J. and Hutchence,K. 1983. Final report of phase 2a geothermal project. Rept. to Govt of Saskatchewan

Vigrass,L.W., Kent,D.M. and Leibel,R.J. 1978. Low-grade geothermal project, geological feasibility study, Regina - Moose Jaw area, Saskatchewan. Earth Phys.Br., Open File 78-4, 79pp+append+diagr+sub.Repts.

Vigrass,L.W., Kent,D.M. and Leibel,R.J. 1979. Low-grade geothermal potential of the Regina - Moose Jaw area, Saskatchewan. Bull.Can Inst.Min.Metall., 72, Oct., 70-76

Vigrass,L.W., Viraghaven,T. and Curtis,F.A. 1984. Preliminary study - use of geothermal energy in wastewater treatment. Rept. to Natl.Res.Council

Vigrass,L.W., Viraraghan,T. and Curtis,F.A. 1984. University of Regina preliminary study use of geothermal energy in wastewater treatment. Rept.to Nat.Res.Council, 45pp+append.

Vtn Consolidated,Inc. 1980 1979 slope stability study - Meager mountain geothermal area. Rept. to B.C.Hydro and Power Authority,.37pp+append.

Ward,S.H. 1981. Report on analysis of dipole-dipole resistivity data, Meager Creek, British Columbia. Rept.to Premier Geophysics

Water management services Ltd. 1984. Study of groundwater flow patterns in Carboniferous sediments of Atlantic Canada Fredericton Subbasin. Earth Phys.Br., Open File 84-11, 60pp+maps

Werner,L.J. 1981. Report on preliminary magnetometer survey Mt.Cayley area southern B.C. Rept.to Geol.Surv. Can.,17pp+figs.

Wiles,T.D. and Roegiers,J.C. 1981. Some applications of the boundary integral technique in stress analysis. Earth Phys.Br., Open File 81-8, 73pp