Overview of Geothermal Energy Resources in Québec (Canada) Mining Enviroments

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Abstract

Rising energy costs, as well as environmental concerns, are driving engineering innovation to reduce energy consumption while remaining competitive, diversify energy supplies and reduce carbon emissions. In that context, geothermal energy represents an alternative to common energy sources. Low-temperature geothermal energy associated with mine sites is gaining acceptance as an economically attractive option for both active mines and nearby communities. Recent studies assessing the geothermal potential of various mining environments have shown promising results. These studies assessed closed and active underground mines as well as flooded open pits and mine waste dumps. Various ground source heat pump designs exist for these systems to exchange geothermal energy using either ground, surface or close-loop water. Different types of mining environments therefore host significant geothermal resources that are readily exploitable with today's technologies. Research and demonstration projects undertaken in the province of Québec have illustrated the benefits associated with the exploitation of geothermal energy in mining environments. For example, the geothermal energy extraction potential of the flooded underground Gaspé Mines, near Murdochville in eastern Québec, was estimated at 765 kW. This sustainable ground load is calculated for a pumping rate of 0.049 m^3/s, with a production temperature of 6.7 °C and a return temperature of 3 °C. In another project, a surface water heat pump system using water flooding a quarry was developed at Saint-Bruno-de-Montarville in southern Québec. The system is used to heat and cool 36 apartments in a condominium complex, having a total surface of 6 039 m^2. Research also began at the South dump of the Doyon Mine in the Abitibi region of Québec to evaluate the technical feasibility of geothermal energy exchange at mine waste dumps. Thermal energy resources contained in the South Dump and the underlying basement are estimated at 1,678,417 GJ from temperature profiles measured in 2007. Additional feasibility studies that recently started at flooded underground mines of British-Colombia, Ontario and the Northwest Territories indicate substantial energy savings. Canada is blessed with abundant natural resources; it hosts a large number of active and closed mines and it is therefore a prime target for developing geothermal energy associated with mine sites. Several research initiatives are expected to further contribute to develop geothermal energy in Canadian mining environments.

Key words: geothermal, energy, low-temperature, mine, water, waste, Québec, Canada.

Nomenclature

C	volumetric heat capacity $[L^{-1}Mt^{-2}T^{-1}]$
H	energy resource $[L^{2}Mt^{-2}]$
T	temperature [T]

where L; length, M; mass, t; time and T; temperature.

Subscripts

a	area
b	bulk
g	ground
r	reference
v	volume

Introduction

The Springhill, Nova-Scotia, Mine Water Project has been in operation since 1989 and pioneered geothermal energy exchange using underground mines in Canada. Groundwater flooding Springhill's Coal Mine is recovered at 18°C and used to heat and cool buildings with heat pumps. Annual energy savings are estimated at 600 000 kWh for the operator, Ropak Can Am Ltd.'s, for on site facilities that cover an area of 7 432 m^2 (CADDET energy efficiency 1992; Jessop et al. 1995). Based on this success, the Geological Survey of Canada inventoried inactive mines in the province of Québec and Nova-Scotia (Arkay 1992). Geothermal energy from mines however attracted little interest in the province of Québec until recently. Current investigation of geothermal energy in a mining environment began at the Town of Murdochville, which conducted a hydrogeological survey in 2004 to identify the geothermal energy extraction potential of the Copper Gaspé Mines that closed in 1999 (Raymond and Therrien 2008). In another project completed in 2006, real estate developers constructed a condominium complex that is heated and cooled by heat pumps using the surface water flooding the Goyer Quarry at St-Bruno-de-Montarville. In the Abitibi region, research is being carried out at the Doyon Gold Mine to evaluate the technical feasibility of geothermal energy exchange at the South Dump. Various mining locations of other Canadian provinces are also being studied for their geothermal potential. Theses include, in British-Columbia, the Britannia Copper Mine (Ghomshei and Meech 2003), in the Northwest Territories, the Con Gold Mine near Yellowknife (Ghomshei 2007) and the Diavik Diamond Mine of the Lac de Gras area as weel as, in Ontario, coal mines near Timmins (Watzlaf and Ackman 2006) and VALE-INCO nickel-copper mines in Sudbury.

Although many studies are being conducted in Canada, the use of ground source heat pump (GSHP) systems in mining environments remains at the early development stage even though this mature technology has proven successful (Geothermal Heat Pump Consortium 1997; John Gilbert Architects 2006a,b). GSHPs appear promising for both active and inactive mines. Flooded underground mines as well as flooded open pits, water retention ponds, mine waste dumps and tailings are considered for geothermal energy exchange.

This manuscript provides an overview of geothermal resources located in mining environments in the province of Québec, Canada. Inventories of the province's closed mines and mine wastes are reviewed. A summary of current research projects in Québec and other Canadian provinces is presented and further research needs are identified.

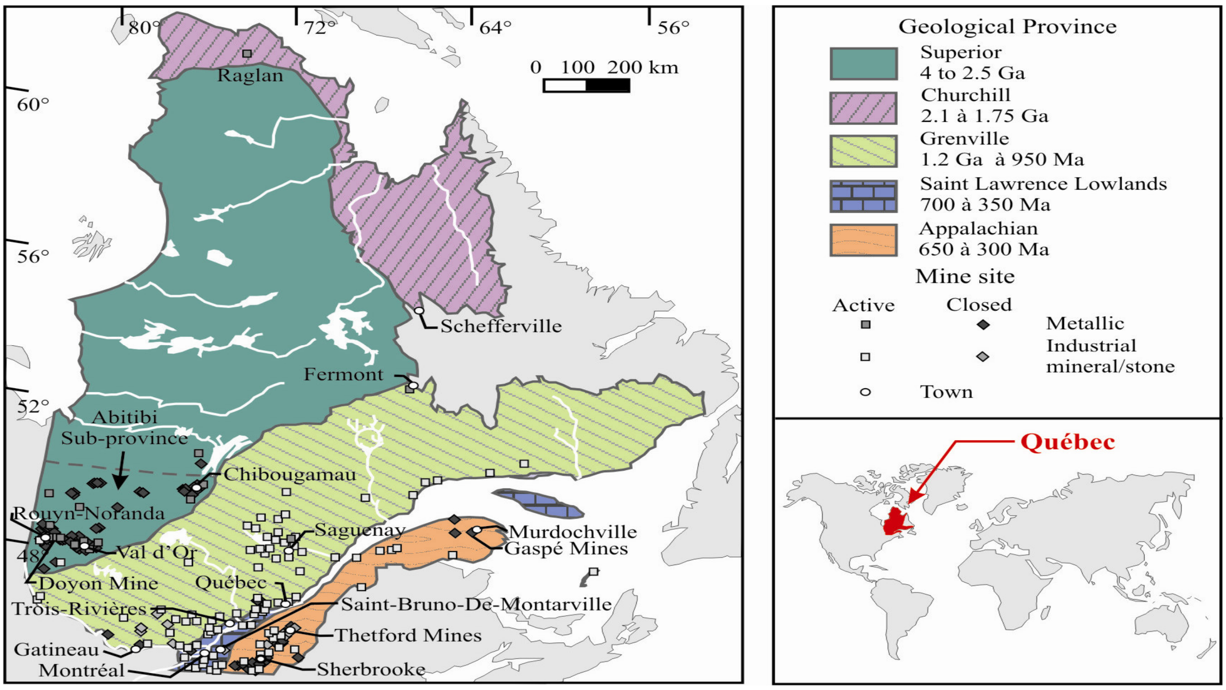
Geological settings and mining history

The province of Québec encloses five main geological provinces (Ministère des Ressources naturelles 1994; Ministère des Ressources naturelles et de la Faune 2007a) and covers a total area of 1,667,926 km^2 (Fig. 10). The Superior Province (4 to 2.5 Ga) contains mostly gneiss and metasedimentary rocks and it covers a third of the province territory. World class copper, gold, zinc, nickel and silver deposits are hosted in the Superior Province, mainly in the Abitibi Sub-province, a volcano-sedimentary Archeen belt. The Churchill Province (2.1 to 1.75 Ga), located in the northern part of the province and predominantly composed of gneiss and metasidementary rocks, contains iron, nickel and copper deposits. The Grenville Province (1.2 Ga to 950 Ma) is a metamorphic belt dominated by gneiss that covers a third of the province territory and hosts major iron and ilmenite deposits. Grenville host rocks and its sedimentary cover have also been exploited for numerous industrial minerals and architectural stones. The Saint Lawrence Lowlands (700 to 350 Ma) to the south are sedimentary platforms with graben structures overlying the Grenville Province. Felsic intrusions that cross-cut the sedimentary platform are exploited for niobium, industrial minerals and architectural stones. The Appalachian Orogene (650 to 300 Ma) further south is made of metamorphosed sedimentary rocks developed at the margin of the Canadian Shield. The orogenic belts of the Appalachian contain important asbestos and copper deposits, industrial minerals and architectural stones. The last glaciations during the Quaternary period shaped the topography and left unconsolidated deposits over parts of the bedrock in almost all regions.

The province's basement hosts attractive settings for metallic and industrial mineral mines of all sizes and various operation types. The hydraulic conductivity of host rocks is generally low and dominantly influenced by fracturation. Crustal heat flow in these old geologic provinces vary from 25 to 65 mW/m^2 with geothermal gradients on the order of 0.01 to 0.02 °C/m (Jessop 1984). Mine geothermal resources are therefore on the low-enthalpy spectrum of the resource and their sizes are dominantly influenced by the nature of mining activities that occurred at a site. A mine can in fact host enhanced resources caused by reworking that occurred during mining. The metallic mines are often associated with sulfide-bearing environments, which may have a positive influence on geothermal resources by releasing heat through sulfide oxidation but, on the other hand, be the source of acid mine drainage that has to be adequately managed. At some minor locality, the calcareous host rock can buffer acid production. GSHPs used at most sites consequently have to be designed with close loops or intermediate plate heat exchangers to cope with the basement nature.

An overview of Québec mining history (Ministère des Ressources naturelles et de la Faune 2007b; Natural Resources Canada 2007; Udd 2000) is given below to outline activities that originally created mine geothermal resources. Early exploitation of iron and sand quarries that left pits in the landscape began during the eighteenth century near Trois-Rivières. Metallic and asbestos mines were later developed in the Southern Appalachian. The first important copper mine, the Eutis Mine, opened near Sherbrooke in 1865. Asbestos deposits were found near the town of Thetford Mines during the late 1870s and exploitation began in 1881 at the Jeffrey Mine. Exploration in the Abitibi region, near Chibougamau and Rouyn-Noranda, started in the early 1900s. Several small copper, gold, iron and asbestos mines opened in the Abitibi, the Appalachian and the Grenville during the 1920-1950 period, coinciding with the beginning of industrialization in these areas. Mining activities were both conducted underground and at surface, leaving excavations and wastes on sites which are now associated with exploitable geothermal resources. Larger exploitations began in the 1950-1970 period. In 1954, iron delivery from Schefferville's mine started, the Copper Gaspé Mines near Murdochville opened, and exploitation of asbestos began at Black Lake near Thetford Mines. With increasing production, mine sites became more organized and better managed to accommodate larger excavations and waste piles forming enhanced geothermal resources. Major mines of the Abitibi, such as the Thompson Bousquet and Doyon mines, opened during the late 1970s. More recently, the LaRonde Gold mine in Abitibi began exploitation in 1988. The Raglan Copper and Nickel Mine located in Northern Québec opened in 1997. Today, much of the metallic mining is concentrated in the Abitibi Sub-province (Fig. 1). Major asbestos deposits of the Appalachian and iron deposits of the Superior and Grenville provinces are still exploited and numerous smaller quarries are active in the Grenville, Saint Lawrence Lowlands and the Appalachian (Fig. 1). Several mines have also closed, requiring major restoration. Both active and restored mines can be targeted for geothermal energy exchange.

Figure 1 *The province of Québec major geological provinces, active and closed mines and towns of interest (modified from Ministère des Ressources naturelles et de la Faune 2007a).*



Mining in Québec spurred the development of small communities, traditionally located a few kilometers away from the mine operations, but generally far from the most populated area of the province in the corridor between Montréal and Québec City to the South. More than a century of mining has left a legacy of underground workings, shafts, open pits, water retention ponds and waste piles that can represent safety and environmental hazards, but also potential low-temperature geothermal energy reservoirs. These potential reservoirs can be exploited for energy exchange using GSHPs to generate significant savings for heating and cooling applications. Economic benefits can help reduce global operation costs of active mines or help to diversify the economy of communities seeking post-mining activities. Associated reduction of carbon emissions can also help lower greenhouse gases production.

Low-temperature geothermal energy resources in the mining environment

Geothermal energy reservoirs at metallic and industrial mineral mines commonly found in Québec can be classified in one of three types according to the GSHP technology that is used: aquifers, surface water bodies or mine wastes. Groundwater heat pumps (GWHP) can exploit aquifers that are located in or near underground mines. Surface water heat pumps (SWHP) can use surface water contained in open pits or water retention ponds. Ground-coupled heat pumps (GCHPs) can be installed in and below mine waste piles.

Aquifers located in or near underground mines show significant low-temperature geothermal energy potential (Bazargan Sabet et al. 2008; Ghomshei 2007; Ghomshei and Meech 2003; Jessop et al. 1995; Malolepszy et al. 2005; Raymond and Therrien 2008; Tóth and Bobok 2007; Watzlaf and Ackman 2006). Enhanced geothermal resources are associated with deep mines, oxidizing host rocks or increased permeability due to mine workings. This last factor is particularly important in geological settings of Québec where most host rocks are of low hydraulic conductivity. Dewatered mines where groundwater is already pumped at active sites and where there is a need to heat and cool infrastructures such as garages, shops and offices are particularly attractive for geothermal development. On the other hand, flooded underground closed mines are common and can be exploited by nearby communities. Arkay (1992) inventoried 165 inactive mines (Fig. 1) and 94 exploration sites where underground excavations occurred. Most underground mines were exploited for metallic minerals except at a few locations near Thetford Mines and Gatineau, where they were exploited for asbestos and industrial minerals, respectively. The inactive underground mines are mostly located in the Superior Province and in the Appalachian Province near the towns of Rouyn-Noranda, Val d'Or, Chibougamau, Sherbrooke and Thetford Mines. A few, small inactive underground mines are also located in the Grenville Province near Gatineau and Québec. Underground mines vary in volume from 10s to more than 100 000 tons of ore removed. An existing geothermal potential was associated with most underground mines that are located close to a community (Arkay 1992). The flooded Gaspé Mines near Murdochville has recently been the host of more detailed studies (Raymond and Therrien 2008) that are outlined below.

Although the geothermal potential has been barely explored, flooded open pit mines and retention ponds used to store runoff water form small to very large surface water bodies suitable for SWHP. Thermal energy could be exchanged using either close loop systems that circulate water and antifreeze in a coil installed in surface water, or open systems that directly use the water. Flooded open pits are commonly found at inactive mines whereas retention ponds are found at both active and inactive mines, especially those of larger sizes later developed. Arkay (1992) mentions the presence of open pits at mine sites without, however, giving much details on pit characteristics. Most inactive open pits are located in the Superior and Appalachian geologic provinces, close to mine communities. The Ministère des Ressources naturelles et de la Faune (2005) maintains a data base on mine wastes, including water retention ponds found at active and inactive mines. The 146 ponds inventoried are mainly located in the Abitibi. Most ponds have neutral pH water but some contain acid water. Each pond covers an area ranging from 5000 to 1,840,000 m^2, for a total of 18,470,000 m^2. Smaller quarries, that are exploited for industrial minerals and architectural stones below the groundwater table, can also form reservoirs. Closed quarries are not inventoried but are expected to be found in the Grenville, Saint Lawrence Lowlands and the Appalachian, with some close to major towns. Development of SWHP that uses water from a flooded quarry came from real estate developers themselves. For example, a luxurious condominium complex heated and cooled with open loop SWHP system using the flooded Goyer Quarry has been constructed in 2006 at Saint-Bruno-De-Montarville (Leblanc, personal communication, 2007). Heat pump units, with capacity ranging from 3.6 to 5.3 kW, have been installed in each of the 36 apartments, for a total heated area of 6 039 m^2. Using intermediate plate heat exchangers, thermal energy is extracted or returned to the quarry which contains 8,064,000 m^3 of water. The system is expected to provide users 40 to 50% energy savings. The developers are currently constructing a second similar condominium and are interested in developing additional complexes.

Mine waste dumps and tailings are typically abundant at major mines and form large piles of granular materials where ground heat exchangers could be installed. These are used with GCHP systems to circulate a mixture of water and antifreeze in close loop piping installed in the ground and exchange heat with the reservoir by conduction. Easily trenchable tailings and hotter oxidizing waste dumps may offer settings to install ground heat exchangers at reduced cost. The homogenous and fine grained nature of tailings allows installation with trenchers that may be cheaper than with conventional backhoe loader. The ground temperature has a strong influence on the required ground heat exchanger length, as can be seen using the standard sizing equation (ASHRAE 2007; Bernier 2000; Kavanaugh and Rafferty 1997). An increase in ground temperature of only 2 °C permits significantly shorter exchanger length for heating mode designs. Waste dumps and underlying host rocks having a warmer temperature due to sulfide oxidation consequently appear to be attractive reservoirs, where cheaper installation costs may be possible. Oxidizing waste dumps are expected at metallic mines of the Abitibi and some localities of the Appalachian. Both waste dumps and tailings typically cover large areas sufficiently to install multiple boreholes or trenches for heat pump systems of high capacity in large buildings. The Ministère des Ressources naturelles et de la Faune (2005) inventoried 555 waste piles in the province Québec. Most of them are located in the Abitibi near Rouyn-Noranda, Val d'Or and Chibougamau, in the Appalachian near Sherbrooke and Thetford Mines and in the Greenville near Scherfferville and Fermont. Each pile covers an area ranging from 1000 to 2,800,000 m^2, for a total waste dump area of 39,760,000 m^2 and a total tailing area of 93,420 000 m^2. About 55 waste dumps are categorized as acidic and are undergoing mineral oxidation, which may raises their temperature compare to surrounding geological formations. A research project that aims to evaluate the technical feasibility of geothermal energy extraction from mine waste dumps has started at the Doyon Mine and is outlined below.

Gaspé Mines project

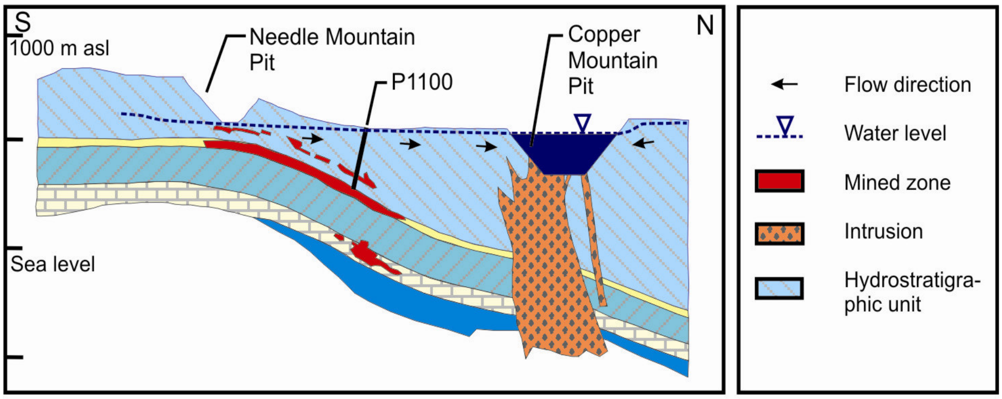
Closure of the Gaspé Mines in 1999 and associated smelter in 2002 has provided an opportunity for the Town of Murdochville (Fig. 1) to explore its geothermal resources. Technical and economic feasibility studies were conducted from 2004 to 2006 to evaluate the mines geothermal potential. The work consisted in site characterization, pumping test, groundwater flow modelling and economic assessment. A complete description of the technical study can be found in Raymond and Therrien (2008) and economical considerations are detailed in the report of Cavanaugh-Morin (2006).

The Gaspé Mines (Fig. 2) are excavated in the Early Devonian Gaspé Superior Limestone Group. Two open pits and three main underground zones were mined. Groundwater flows toward the Copper Mountain Pit where water level has been rising since mine closure. Thermal energy resources contained in the mine was estimated to 61,000 GJ using the local geothermal gradient (0.011 °C/m) and the estimated water volume contained in underground workings (3,732,300 m^2). This energy is the equivalent of that contained in 10,914 oil barrels (US) assuming that burning one crude oil (kerosene) barrel releases 5589 MJ. Mine water energy is being renewed by the earth heat flux locally evaluated to 51 mW/m^2.

A pumping test was performed in the former mining shaft P1100 (Fig. 2) to determine underground workings and host rock hydraulic properties. Pumping was conducted for 3 weeks at a rate averaging 0.062 m^3/s (3720 l/m) and a maximum drawdown of 3.63 m was observed. The hydraulic conductivity of the workings and host rock was estimated equal to 2.3 X 10^{-2} m/s and 4.5 X 10^{-5} m/s, respectively, using groundwater flow modelling. Pumped water temperature measured during the test averaged 6.7 °C. Groundwater flow modelling was subsequently performed to simulate pumping for geothermal heating at the town industrial park. To estimate the site geothermal potential, the modelled drawdown surface was calculated to evaluate the captured energy, which was compared to the energy that can be extracted using heat pumps. The sustainable energy extraction rate was estimated to 765 kW for a pumping rate of 0.049 m^3/s (2940 l/m), assuming that the 6.7 °C pumped water temperature can be lower to 3 °C using a GWHP system.

The Town of Murdochville is interested in developing a geothermal energy distribution network at its industrial park, which is located over the mine workings. Groundwater could be pumped from a former mining shaft and delivered to buildings equipped with their own heat pump systems having a total capacity of 822 kW. The coefficient of performance at heat pump units assumed for the economic assessment varied with water temperature from 4.4 to 3.4 such that the ground load remains below the site geothermal potential. Investment costs associated to the construction of such a network are evaluated at 523,124 $CAN. Annual energy savings provided with GWHPs, using the network at its full capacity, is on the order of 2,494,500 kWh, offering net energy savings of 143,600 $CAN annually and a pay back period of 3.6 years. The town is currently looking for partnership to develop their geothermal resources.

Figure 2 *Gaspé Mines schematic cross-section showing hydrostratigraphic details of units (Raymond and Therrien 2008). Section redrawn after Bernard and Procyshyn (1992). ICove: Indian Cove Formation; SHeap: Ship Head Formation; A-limestone: argillaceous limestone; C-mudstone: calcareous mudstone; Qz: quartz; Ca: calcite; Ab-Mi: albite-microcline. * Average mineralogy inferred from geochemical data (Wares and Berger 1993). ** Porosity estimated on the basis of the rock type classification proposed by Freeze and Cherry (1979). Bulk thermal conductivity λ_b and heat capacity Cp_b calculated from mineralogy with (Brailsford and Major 1964) and (Waples and Waples 2004a,b).*



Hydrostratigraphy

Color	Unit	Corresponding rock formation	Dominant rock type	Mineralogy (wt%)* Qz	Ca	Ab-Mi	n**	λ_b [W/(m K)]	Cp_b [J/(Kg K)]
	U1	ICove-SHead	C-mudstone	60	15	25	0.05	4.77	792
	U2	SHeap	A-limestone	30	30	40	0.1	3.36	872
	U3	Forillon	C-mudstone	50	20	30	0.05	4.33	794
	U4	Forillon	A-limestone	20	40	40	0.1	3.12	879
	U5	Forillon	C-mudstone	60	20	20	0.05	4.87	797

Doyon Mine project

The Doyon Gold Mine (Fig. 1) has been operating since 1978. The exploitation started in two open pits but mining has been conducted underground since 1989. The South Dump (Fig. 3) was constructed from 1983 to 1987, without significant modifications since. Today, the temperature of this pile of waste rocks is significantly higher than the surrounding host rock temperature, which makes it attractive for geothermal energy exchange. At the site, waste rocks cover an area of 549,400 m^2 and has a maximum thickness of about 35 m. The dump is dominantly constituted of sericite schist fragments deposited on a silty overburden. The underlying host rocks are mostly metavolcanics. Acid mine drainage was first observed in 1985 with peak production near 1988. Effluents were characterized at that time by a pH near 2 and total dissolved solids of about 200,000 mg/l (Lefebvre et al. 2001a). Extensive environmental characterization and numerical modelling that aimed to better understand the production of acid mine drainage was conducted during the 1900's (Gélinas et al. 1994; Lefebvre 1994; Lefebvre et al. 2001a; Lefebvre et al. 2001b). Recent numerical modelling of sulfide oxidation and groundwater flow using data from the South Dump brought a better understanding of the physicochemical processes responsible for acid mine drainage (Molson 2005). Research is currently conducted by Université Laval to evaluate the technical feasibility of geothermal energy exchange at the South Dump.

Figure 3 *Topographical map of the South Dump at the Doyon Mine showing the location of observation wells.*

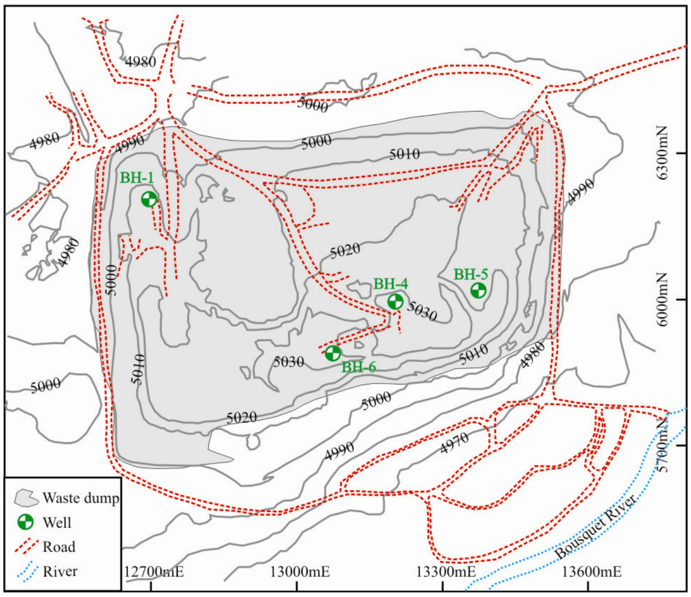
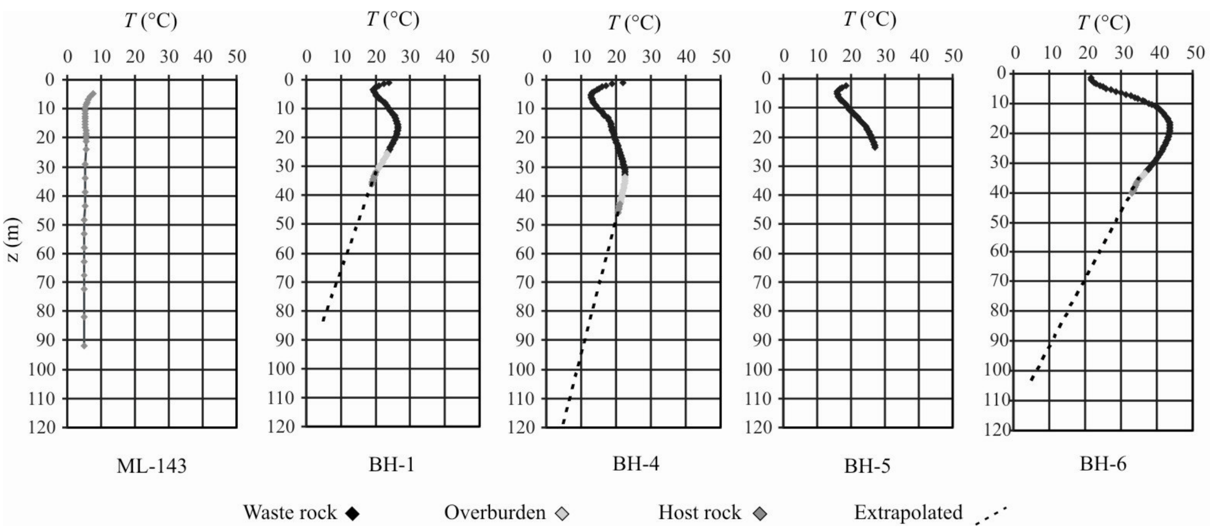


Figure 4 *Temperature profiles measured in an exploration hole (ML-143) more than 1 km away from the dump and in monitoring wells (BH-1, BH-4, BH-5, BH-6) installed at the South Dump of the Doyon Mine.*



Temperature measurements made during the 1900's indicated that the dump internal temperature ranged from 20 to 65 °C (Choquette and Gélinas 1996; Lefebvre et al. 2001a). The temperature has since been slowly decreasing. Additional temperature measurements were performed in 2007 at the existing boreholes located in Fig. 3. Only four of the seven boreholes that were drilled during the 1990's remained on site. These boreholes are observation wells drilled through the waste pile and about 6 to 13 m of the underlying overburden and host rock. BH-5 is however drilled in the waste rock only and does not cross cut all the pile thickness. A flexible liner was installed in the boreholes that were filled with water. Temperature was measured in the water with a thermistor having a resolution of 0.05 °C and an accuracy of 0.1 °C. An additional temperature profile was measured in an exploration diamond drilled hole (ML-143) located more than 1 km away from the waste dump, to evaluate the undisturbed ground temperature. All measurements are shown in Fig. 4. The waste dump has a temperature ranging from 13 to 44 °C at depths below 5 m, which is significantly above the mean undisturbed ground temperature of 5.1 °C. Temperature of the overburden and host rock below the waste pile is also warmer, with temperature ranging from 36 to 18 °C in the first 6 to 13 m below the waste pile. The temperature gradient is estimated below the drilled depth using the slope of the gradient measured in the host rock. Using this estimated gradient, the undisturbed ground temperature is reached at depth of 81 to 116 m.

The thermal energy resources stored in the South Dump are calculated below. The energy resource contained per unit volume H_v at wells BH-1, BH-4 and BH-6 is initially calculated for each temperature measurement below 5 meters with:

$$H_{\mathrm{v}} = (T_{\mathrm{g}} - T_{\mathrm{r}})C_{\mathrm{b,g}} \qquad \text{eq. 1}$$

where T_g is the ground temperature, T_r is the reference temperature and $C_{b,g}$ is the bulk volumetric heat capacity of the ground. The upper 5 meters of waste dump is not considered because its temperature significantly fluctuates with daily and monthly atmospheric temperature variations. The undisturbed ground temperature is used for T_r, which assumes that thermal energy resources are available until the waste dump and underlying material is cooled to 5.1 °C. Temperatures measured in the waste pile, the overburden and host rock and temperatures extrapolated in the host rock are used for T_g. Volumetric heat capacities of 1.98 $MJK^{-1}m^{-3}$, 3.02 $MJK^{-1}m^{-3}$ and 2.34 $MJK^{-1}m^{-3}$ for the waste dump, overburden and host rock, respectively, are reported by Lefebvre (1994) and used here. The energy resource contained per unit area H_a is then calculated using:

$$H_{\mathrm{a}} = \frac{(H_{\mathrm{v,i+1}} + H_{\mathrm{v,i}})}{2}\Delta z \qquad \text{eq. 2}$$

where Δz is the interval between two temperature measurements (i+1 and i). The H_a values are summed over the well and extrapolated depths to determine the energy contained per unit surface at each well. Energy at each well is averaged and then multiplied by the waste dump surface (549,400 m^2) to estimate the total energy contained in the South Dump and underlying materials. Calculation details are outlined in Table 1.

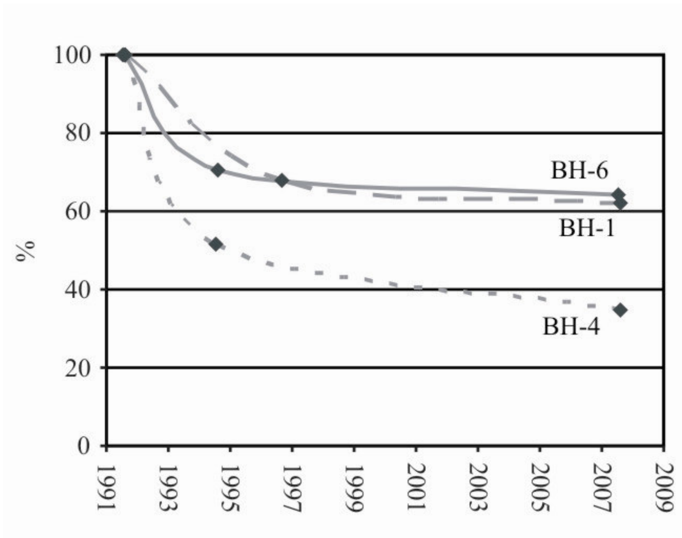
***Table 1** Doyon Mine South Dump energy resources*

C_b waste dump[1] ($MJK^{-1}m^{-3}$)	1.98
C_b overburden[1] ($MJK^{-1}m^{-3}$)	3.02
C_b host rock[1] ($MJK^{-1}m^{-3}$)	2.34
H_a BH-1 (MJm^{-2})	2003
H_a BH-4 (MJm^{-2})	2647
H_a BH-6 (MJm^{-2})	4514
H_a average (MJm^{-2})	3055
Waste dump area (m^2)	549,400
Total energy resources (GJ)	1,678,417
Equivalent oil barrels (US) 5589 MJ/barrels	300,307

1- (Lefebvre 1994)

This resource base calculation indicates that total energy host in the South Dump and underlying materials (i.e. accessible and inaccessible heat) is equal to 1,678,417 GJ, which represents the amount of energy that is released by burning 300,307 oil (kerosene) barrels (US). The waste dump energy is slowly dissipated by heat conduction. The evolution of the energy resources in the dump can be evaluated with temperature measurements collected site from 1991 to 1996 (Choquette and Gélinas 1996). The relative energy decrease (Fig. 5) is calculated in the waste dump only because of limited former data assuming that the 1991 temperature represented near peak values (i.e. 100%). The decrease of energy resources was rapid during the first five years and has slowed down during the last ten years, suggesting that significant resources are still available for the next decades.

Figure 5 *Relative energy decrease at the South Dump of the Doyon Mine.*



Part of the South Dump thermal energy resources could be exploited with a GCHP system using ground heat exchangers. The energy extracted could be used for space heating. The GCHP system could also be used for cooling, and the heat released at the dump site could contribute to preserve energy resources for a longer period. Numerical modelling of heat exchange at the South Dump is planned to evaluate the technical feasibility of such exploitation.

Other Canadian projects

Geothermal projects in mining environments have been undertaken in other Canadian provinces. Studies focused on the potential and feasibility of geothermal energy exchange at underground flooded mines of various natures. The Copper Britannia Mine in British-Colombia was investigated by Ghomshei and Meech (2003). It was proposed to use the mine water that is resurging at 15 °C and at a pH of 4 to 4,5 to heat homes of the nearby community. A district heating system having a capacity of 1.2 to 5 MW could be operated with a power supply of 0.24 to 1 MW only. Acid resistant plate heat exchangers would be necessary to cope with the water acidity. Investment costs of a district heating system at Britannia were evaluated at 2 to 2.5 M$CAN with annual net energy savings of 25 to 35 k$CAN giving a payback of about 5 to 8 years.

The Gold Con Mine of the Northwest Territories that closed in 2003 can potentially be used for heat exchange with a system supplying buildings at the city of Yellowknife (Ghomshei 2007). A demonstration project having a 300 kW heating capacity and a total power supply of 90 kW could be developed using water from a single mining shaft. Capital costs of such a demonstration project are estimated to 768 k$CAN with annual net energy savings of 95 k$CAN giving a pay back period of about 8.1 years. Heating capacity may be expanded to 2 MW (0.4 MW power supply) using water that can be above 40 °C in deeper mine levels.

Diamond mines near the Lac de Gras area of the Northwest Territories are being studied by The Earth Mine Energy Research Group (EMERG) of McGill University. This area, known as the third biggest diamond producer of the world, is the host of three actives mines (Jericho, Ekati and Diavik) and two

mine projects planned to be developed (Gahcho Kue and Snap Lake). Mining operations in kimberlite pipes are both conducted at surface and underground. High water inflow in these fractured igneous rocks has to be adequately managed in excavations. At the underground Diavik Mine, water is pumped at an average rate equals to 0.423 m^3/s (27,778 l/m) and a temperature around 6 °C. Pumped water could be adequately managed to provide geothermal heating for operational mine infrastructures.
Ontario's coal mines near Timmins were identified potential geothermal resources. A study briefly reported by Watzlaf and Ackman (2006) indicates that 12 to 13 °C water at depth of 200 to 250 m could be used to heat an exposition/convention center.
Nickel and copper mines of Sudbury in Ontario has also been targeted by EMERG for further geothermal studies. One of the six VALE-INCO mines in this region has a depth of more than 1200 m and is a potential location for geothermal development. Temperature in the deepest part of the mine is assumed equal to 25 °C. Groundwater infiltrates the underground mine at high rates through the brecciated Archean basement. Mining operations are expected to proceed to deeper levels. Dewatering mine water could be used with GWHP to heat mine infrastructures and homes of Sudbury's communities having a total population of 160,000 residents.

Conclusions

The mining sector has an opportunity to make an additional step toward sustainability using the abundant geothermal resources of mine sites. 165 closed mines, 146 retention ponds and 555 mine waste piles have been inventoried throughout the province of Québec. All these represent settings with potential geothermal resources that can be exploited with GSHPs to provide energy savings and reduce green house gases emissions. Such major resources are typically far from populated areas but can be developed locally to diversify energy supplies. Active mines are targeted potential users because of their energy needs and close proximity. Mining communities facing site closure have so far shown the most interest to develop this resource.
Original researches have been initiated to evaluate the geothermal potential of mining environments. Work carried at the Gaspé Mines near Murdochville during a feasibility study helped to define the hydraulic conductivity of underground workings and the site potential. The project reported at the South Dump of the Doyon Mine first evidenced the large geothermal resources associated with an oxidizing waste dump. Various initiatives undertaken in Canada have also contributed to resource characterization and feasibility assessment.
The capital cost associated with GSHP installation is greater than that of conventional systems resulting in longer pay back period. Additional research efforts can be conducted to minimize GSHP installation costs and promote the use of this technology. Abundant resources of the mining environment, being easily accessible and/or having enhanced characteristics such as host rock permeability or temperature, offer possibilities to install GSHP at lower cost. Pay back of projects reported in this manuscript was down to 3.6 to 8.1 years. Other mines can allow reduced installation costs. Inventories of geothermal resources in mining environments could therefore be improved and updated to target the most attractive sites. Although some mines have been extensively characterized from an environmental perspective, there is a lack of data on temperature and thermal properties at most sites. Additional field characterization at some promising locations will provide data to design economical GSHP systems. Field testing methods of thermal properties could be improved to obtain better data in diversified environments allowing more precise designs. Heat exchange modelling remains useful to evaluate feasibility and optimize designs. Analytical and numerical modelling tools could be improved to simulate heat exchanges in complex environments such as mine sites. Research collaborations with the mining sector and affected communities represent the first step toward demonstration projects to promote the use of GSHP in mining environments.

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