Geothermal Systems in Shield Rocks and Permafrost Regions; Examples from Northern Québec

Jasmin Raymond[1], Chrystel Dezayes[2], Edgardo Alvarado[1], Evelyn Gunawan[3]
Felix-Antoine Comeau[1], Inès Kanzari[1], Mafalda M. Miranda[1], Nicolò Giordano[1]

[1]INRS - Institut national de la recherche scientifique, Centre Eau Terre Environnement, Québec, Canada
[2]BRGM – Bureau de recherches géologiques et minières, Orléans, France
[3]Reykjavik University, Island School of Energy, Reykjavik, Island

YGF Geothermal Energy Workshop - November 23rd

Centre d'études nordiques

Institut nordique du Québec
Together for the North

INRS
UNIVERSITÉ DE RECHERCHE

Energy needs of remote regions

Communities

- ~50 % of energy consumed is for space and water heating
- Single diesel furnaces provide heating to each building
- 0.16 $/kWh thermal for subsidized diesel at 1.4 $/L

Mines

- Heating of underground workings can be required
- Fossil fuels are mainly used to produce heating
- 0.06-0.29 $ heating per ton extracted (MERN, 2016)

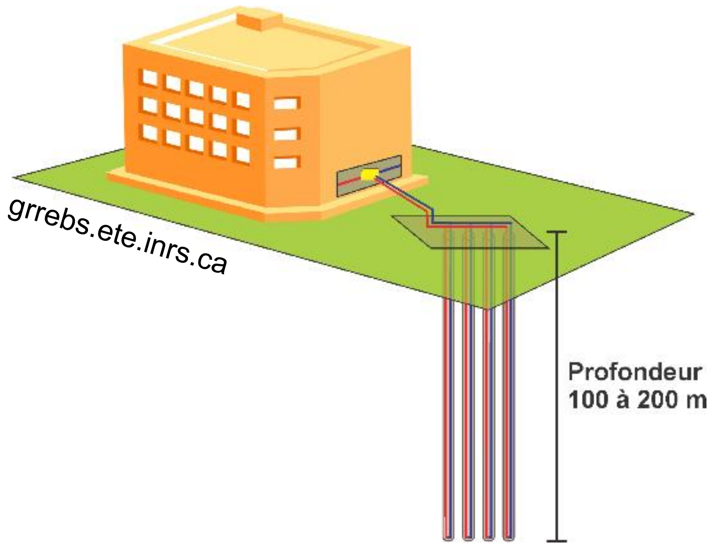
Alternatives to fossil fuels

Heat production

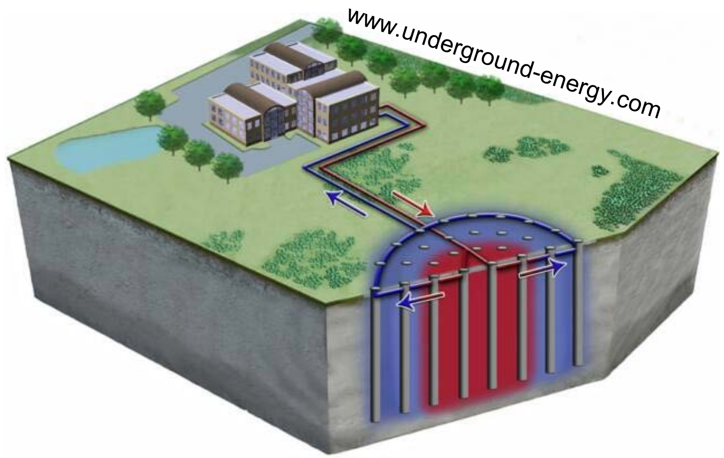
- Heat recovery
- Biomass
- Waste to energy
- Geothermal energy
    - Ground source heat pump (shallow)
    - Thermal energy storage (shallow)
    - Enhanced geothermal system (deep)

Overview of possible geothermal systems

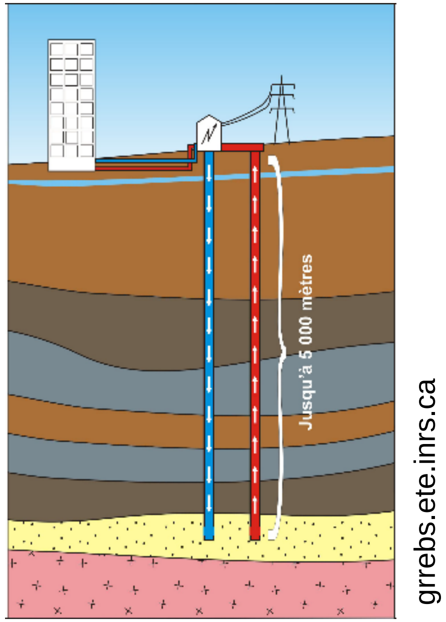
Ground source heat pump (GSHP)
- Absorption (combustible)
- Electric + Solar PV
- Borehole heat exchangers (100-200 m)
- Low temperature (-10 to 10 ºC)



Thermal energy storage (TES)
- Seasonal
- Solar thermal/PV
- Borehole heat exchangers (30-50 m)
- Moderate temperature (10 to 50 ºC)

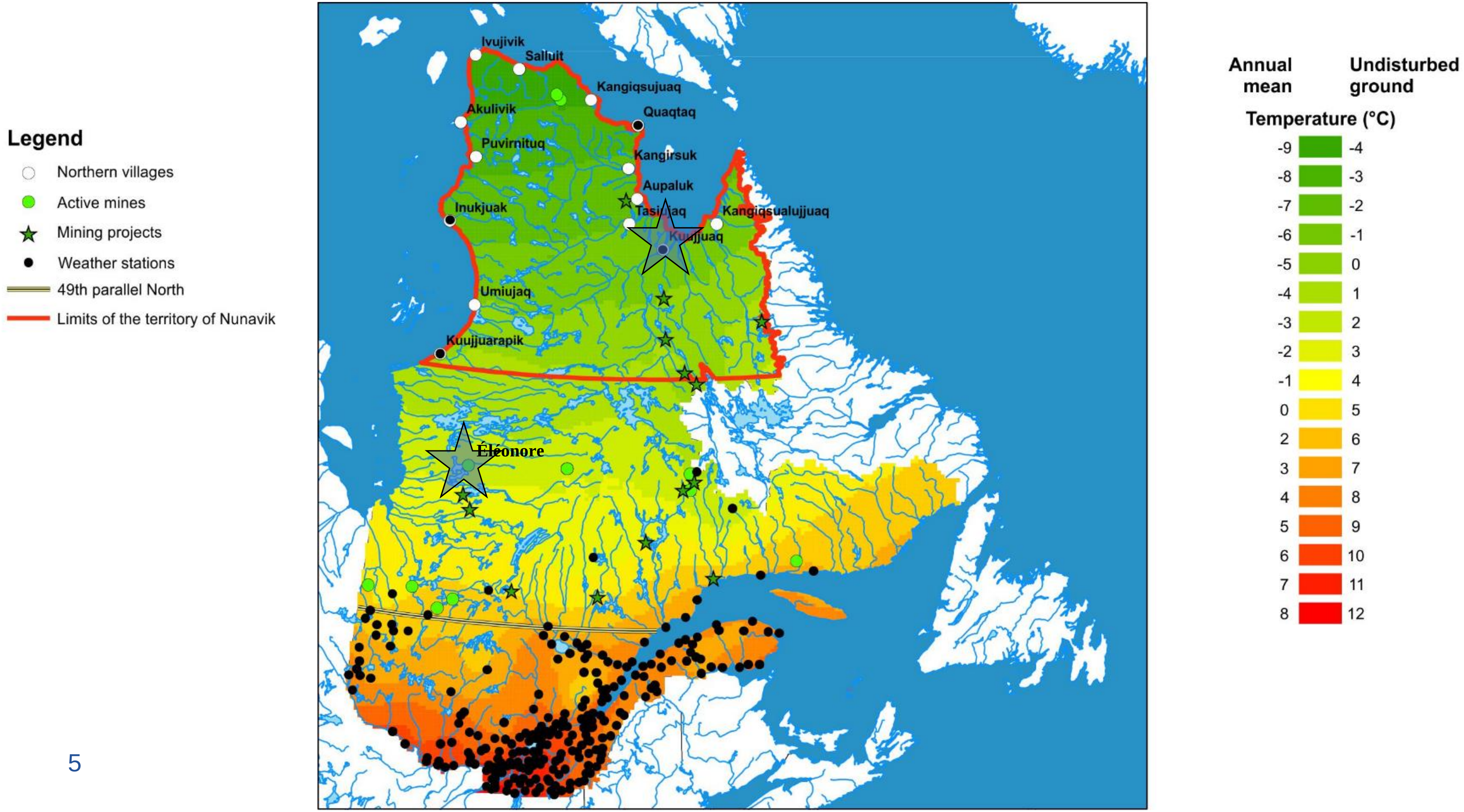


Enhanced geothermal systems (EGS)
- Hydraulic stimulation
- Deep wells (3 – 5 km)
- High temperature (50 to 100 ºC)

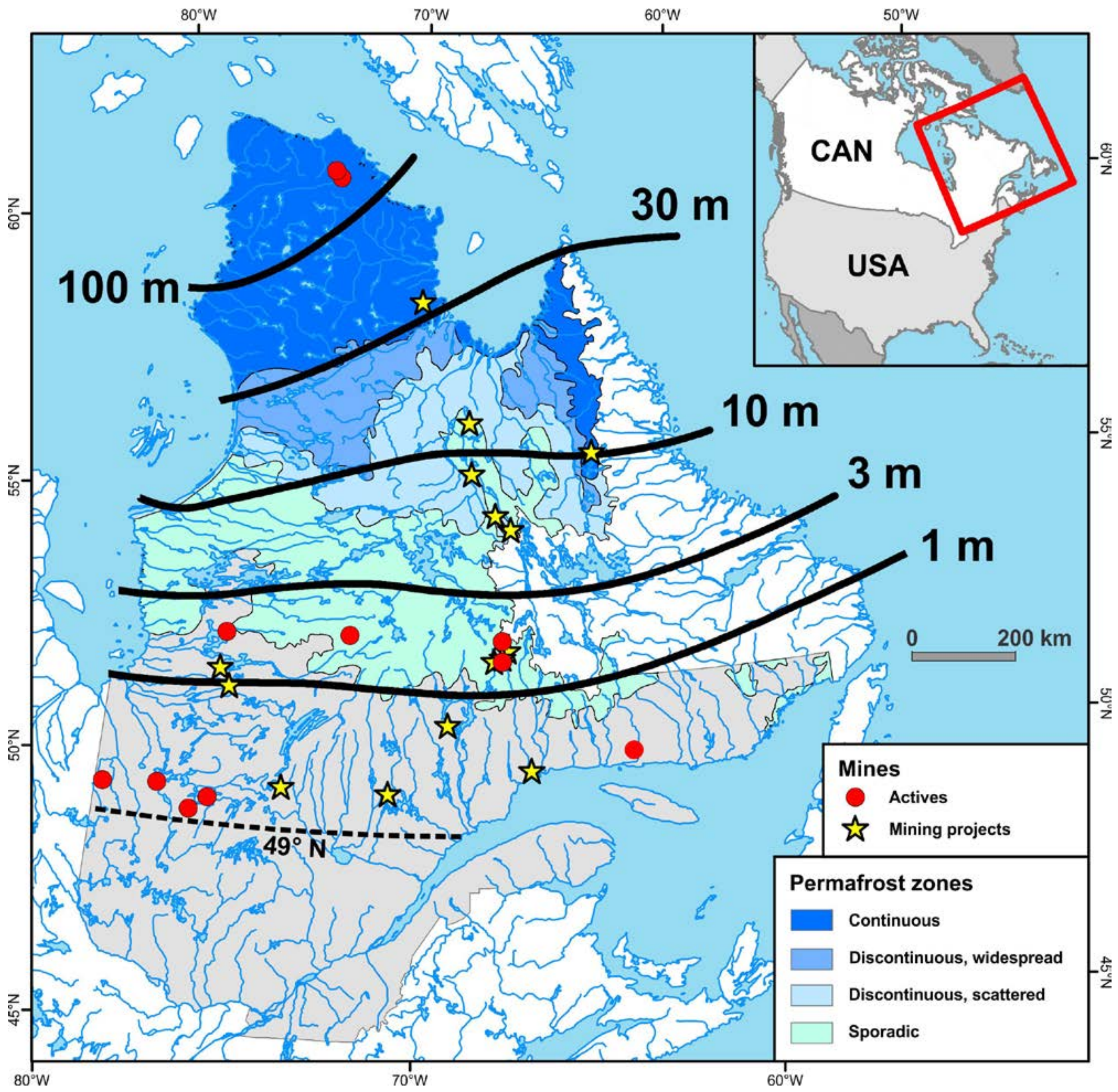


Geographical setting

Comeau et al. (2017)

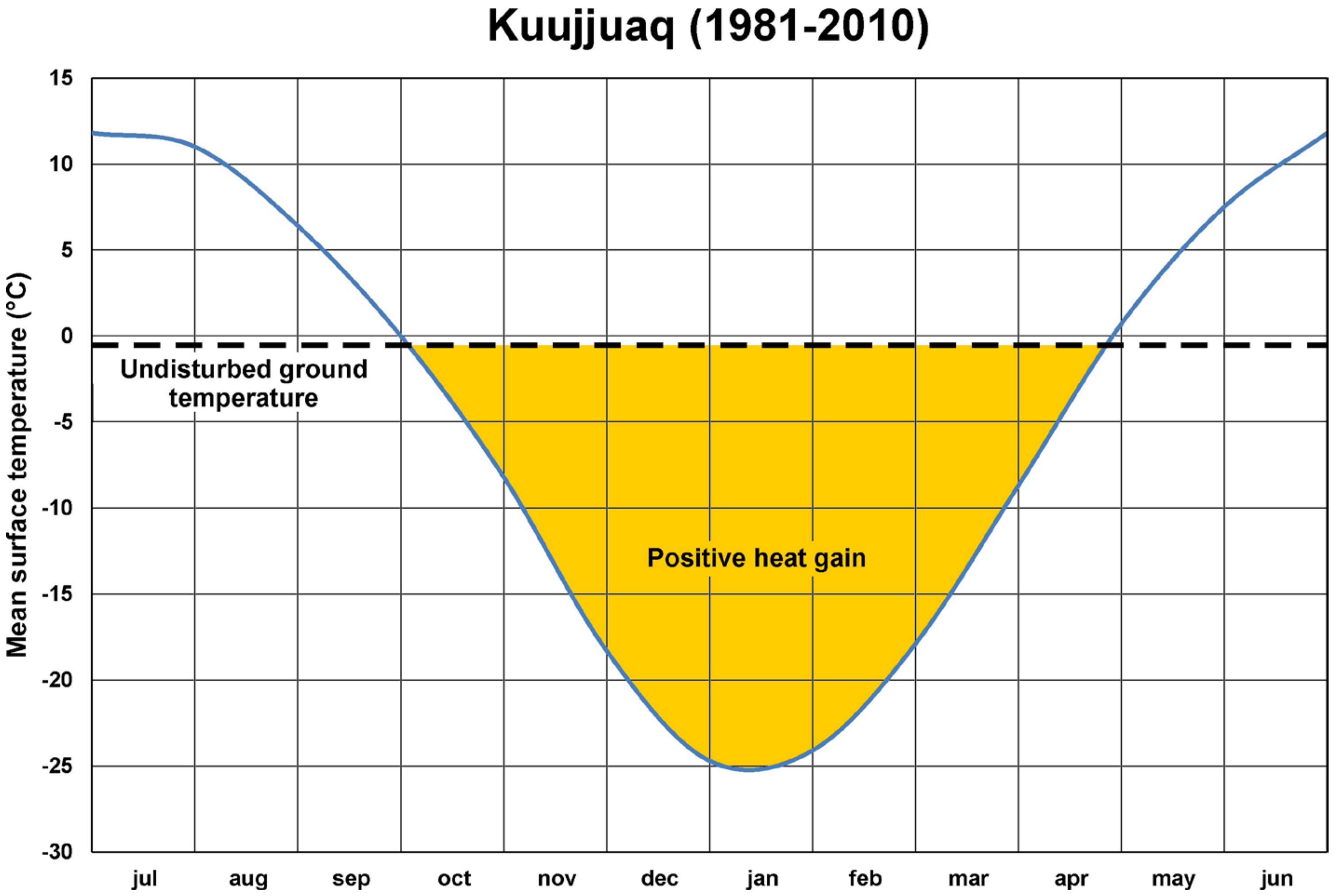


Permafrost distribution

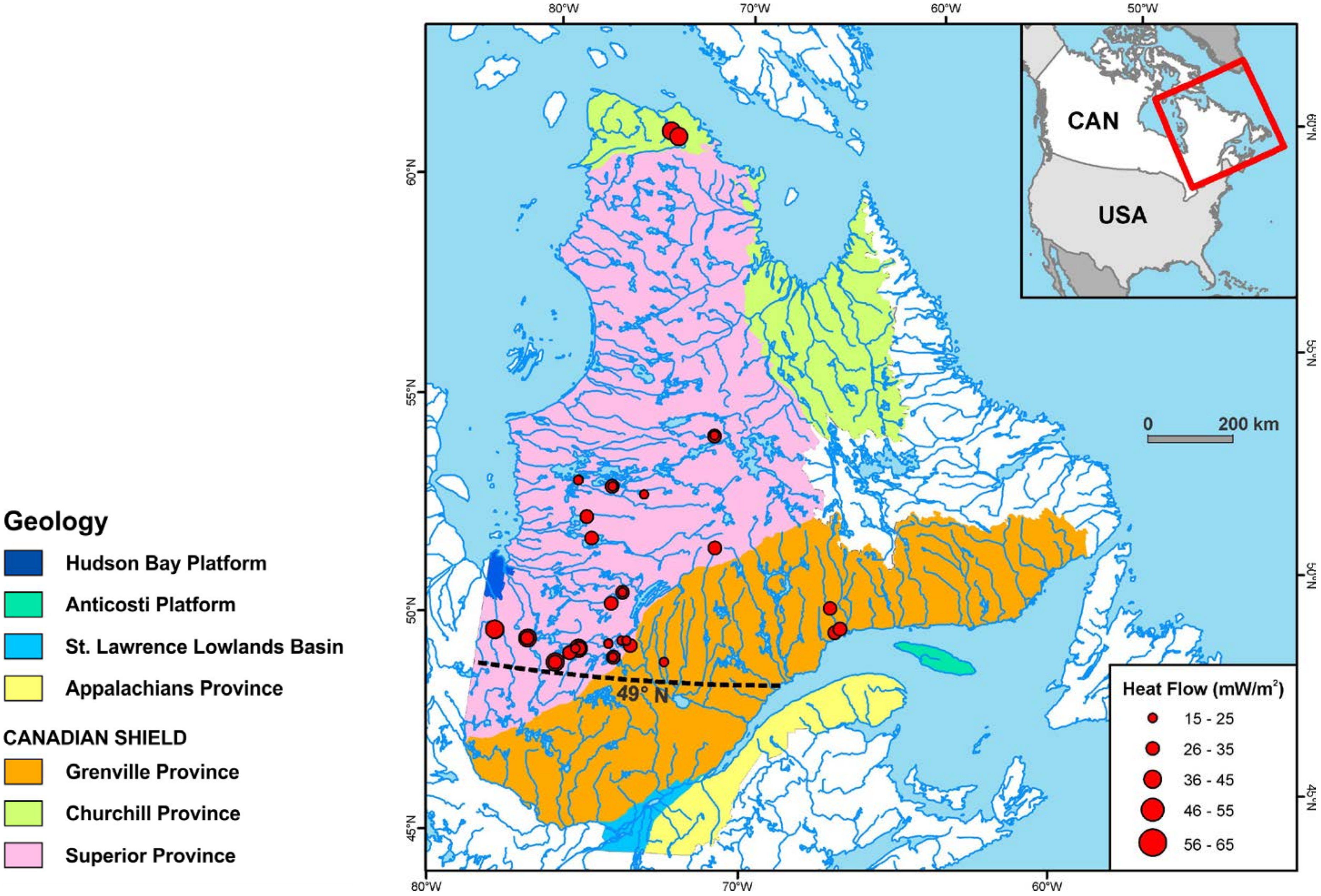


Lemieux, J.-M., et al., 2016. **Groundwater occurrence in cold environments: examples from Nunavik, Canada**. Hydrogeology Journal, Volume 24, Issue 6, pp 1497–1513.

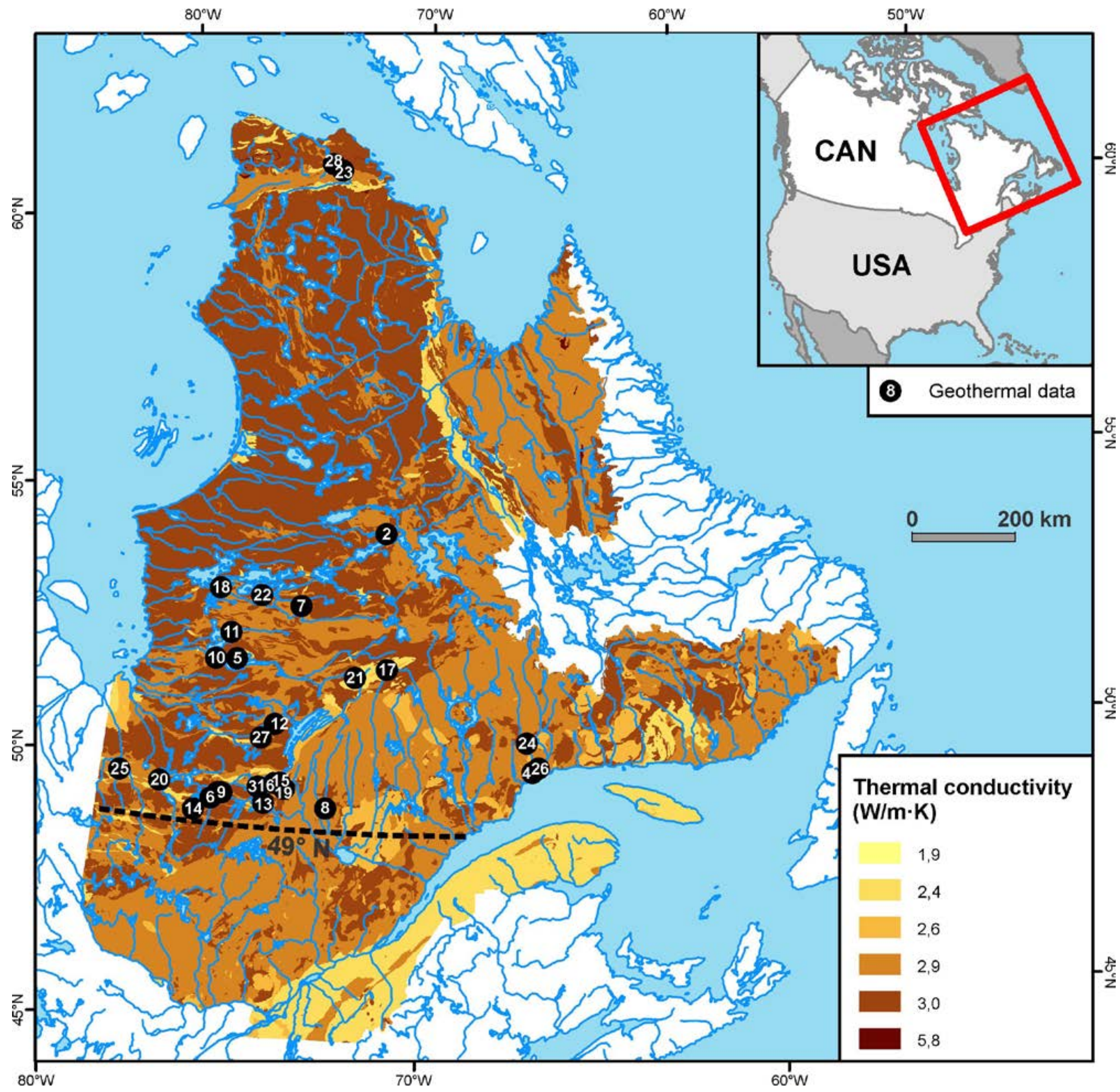
Temperature balance at the ground surface



Geology and heat flow



Geology and thermal conductivity distribution

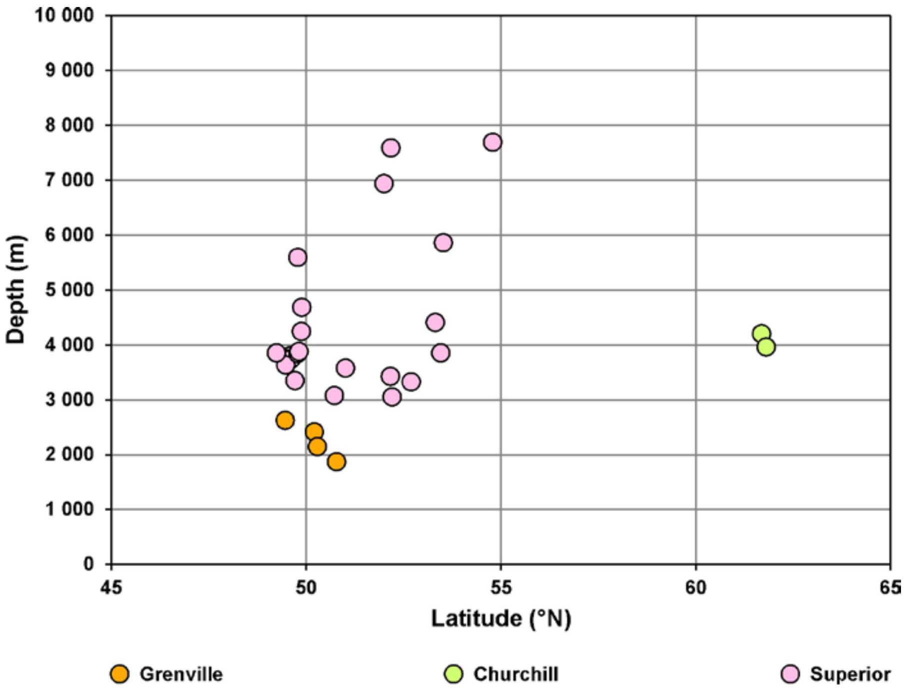


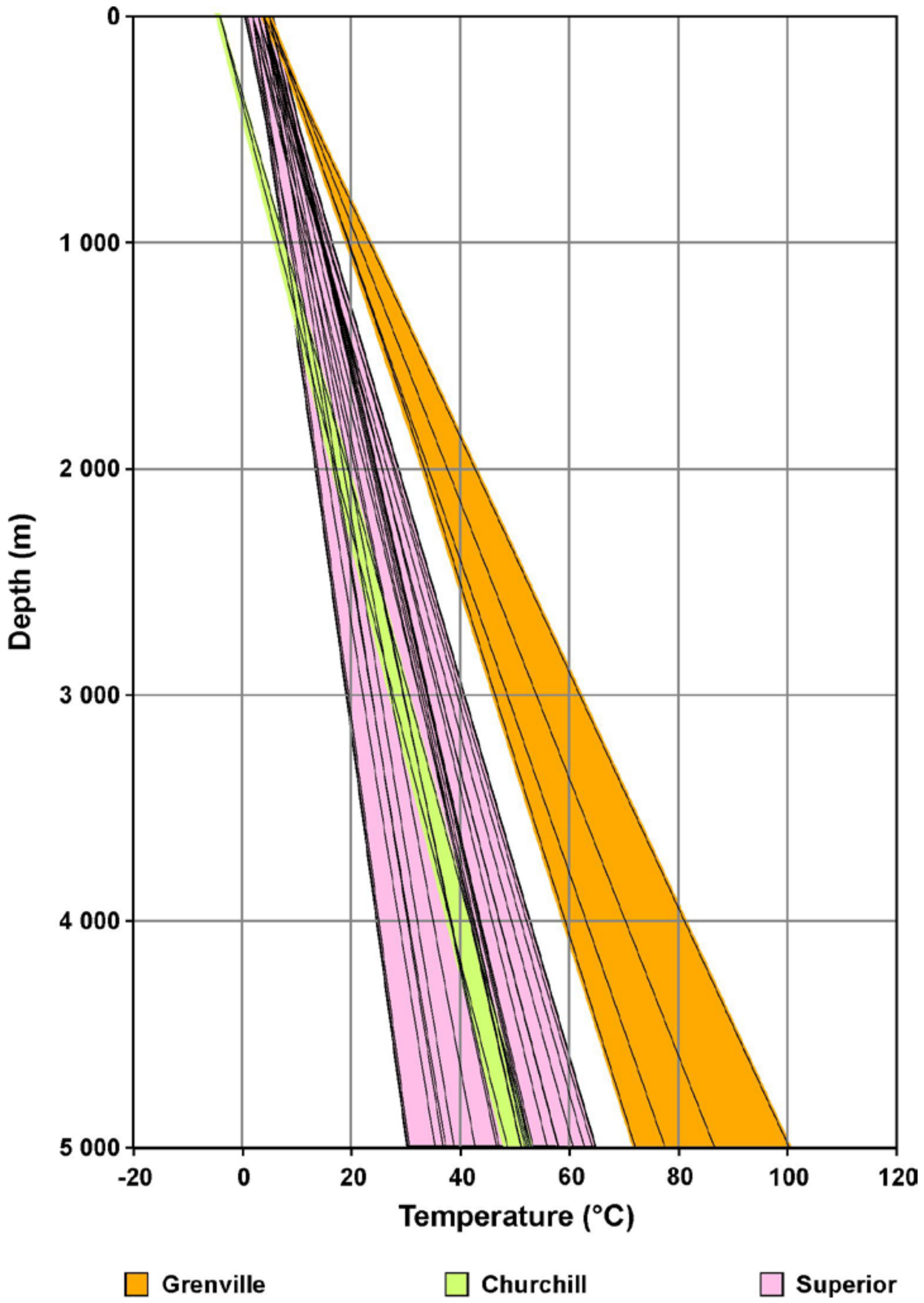
Extrapolated temperature

$$T_z = T_0 + \left(\frac{Q_0 \cdot z}{\lambda}\right) - \left(\frac{A \cdot z^2}{2\lambda}\right)$$

Tz (°C) is the temperature at depth z
T_0 (°C) is the undisturbed ground temperature
Q_0 (W/m^2) is the surface heat flow
z (m) is the depth below surface
λ (W/m·K) is the effective thermal conductivity
A (W/m^3) is the average heat generation rate.

Depth to reach 40°C





Is geothermal system operation feasible is this subarctic climate?

What kinds of benefits can it generate?

8500 HDD_{18}

58 ºN latitude

-5.8 ºC mean temp.

7000 HDD_{18}

52 ºN latitude

-3.9 ºC mean temp.

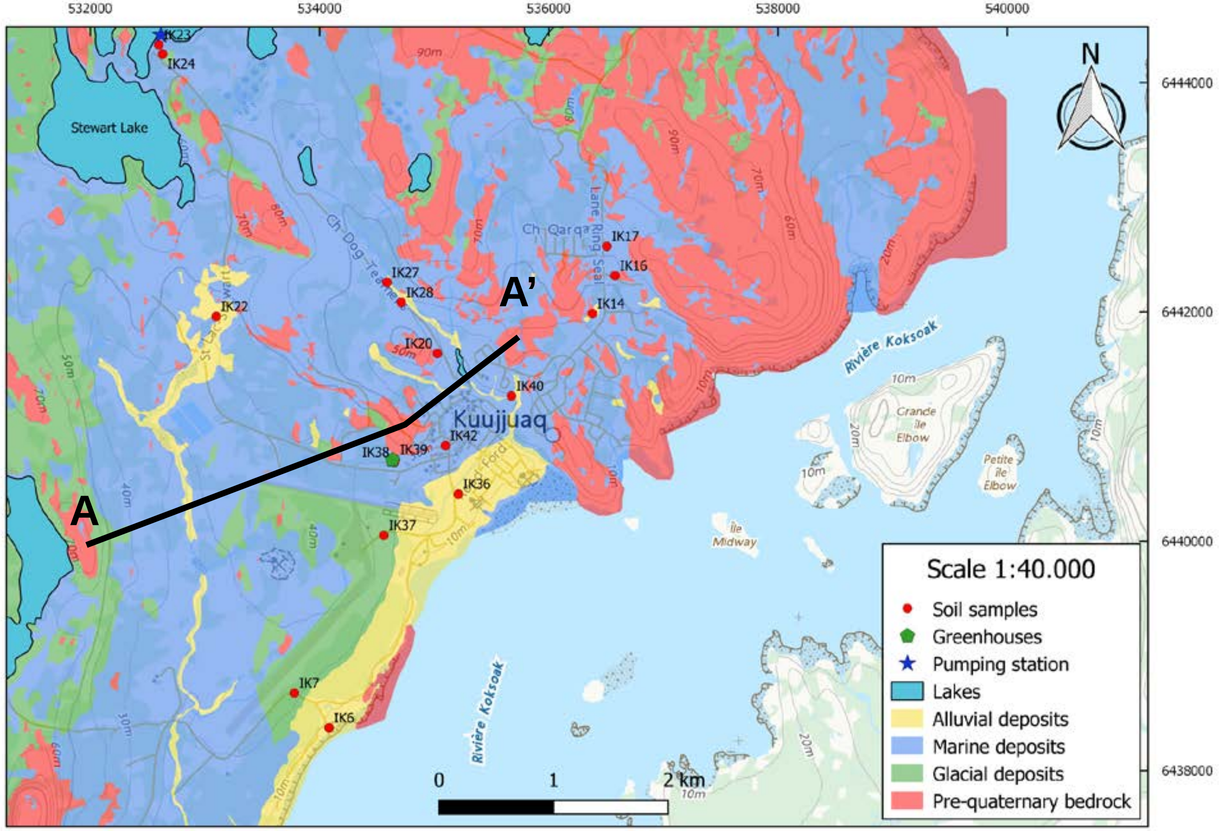
https://ykonline.ca

8300 HDD_{18}

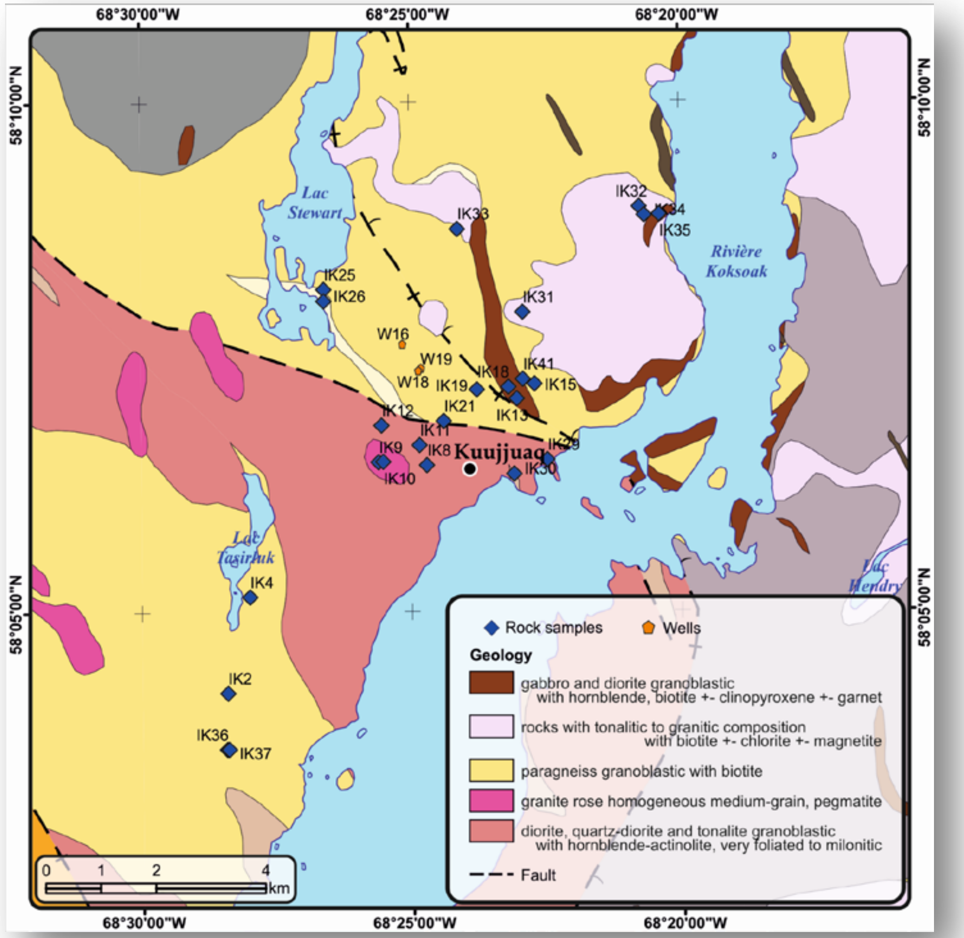
62 ºN latitude

-4.6 ºC mean temp.

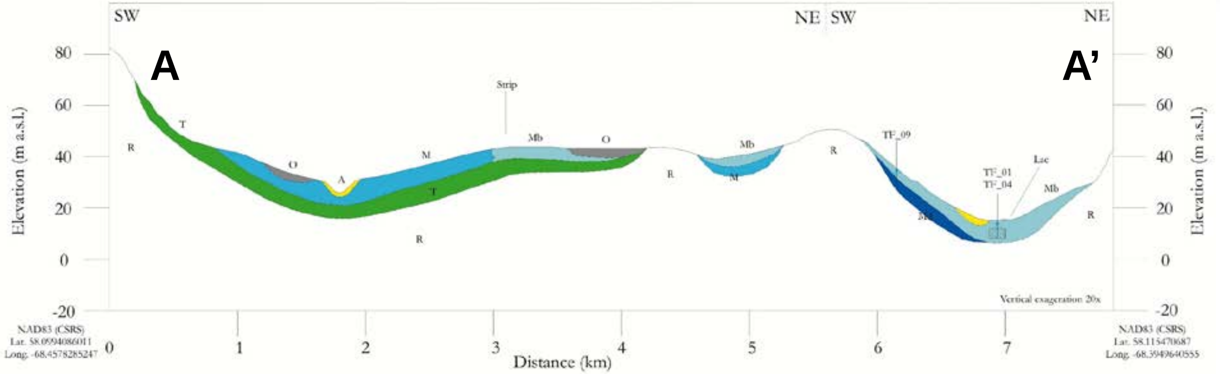
Kuujjuaq geological setting



Quaternary sediments



Bedrock



Methodology

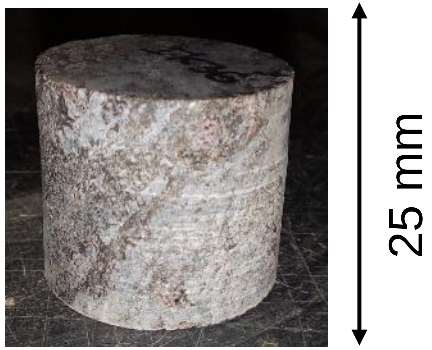
Shallow systems

- Geophysical surveys (permafrost characterization)
- Permeability tests
- Rock and soil sampling
- Laboratory analysis (thermal conductivity, heat capacity)
- Temperature-depth profiles
- Numerical simulations

Methodology

Deep resources

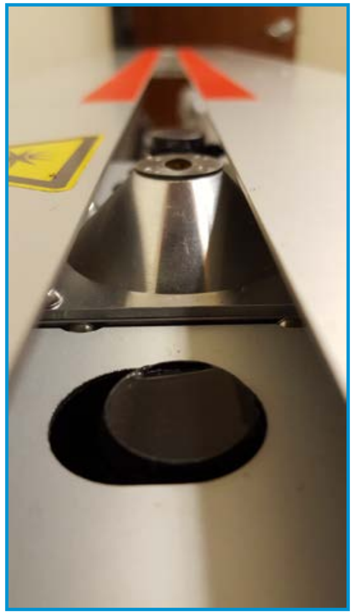
- Temperature-depth profiles
- Fracture network characterization at outcrops
- Rock sampling
- Laboratory analysis (thermal conductivity, heat capacity, radiogenic heat production)
- Analyses of geothermal gradient and heat flux
- Numerical simulations



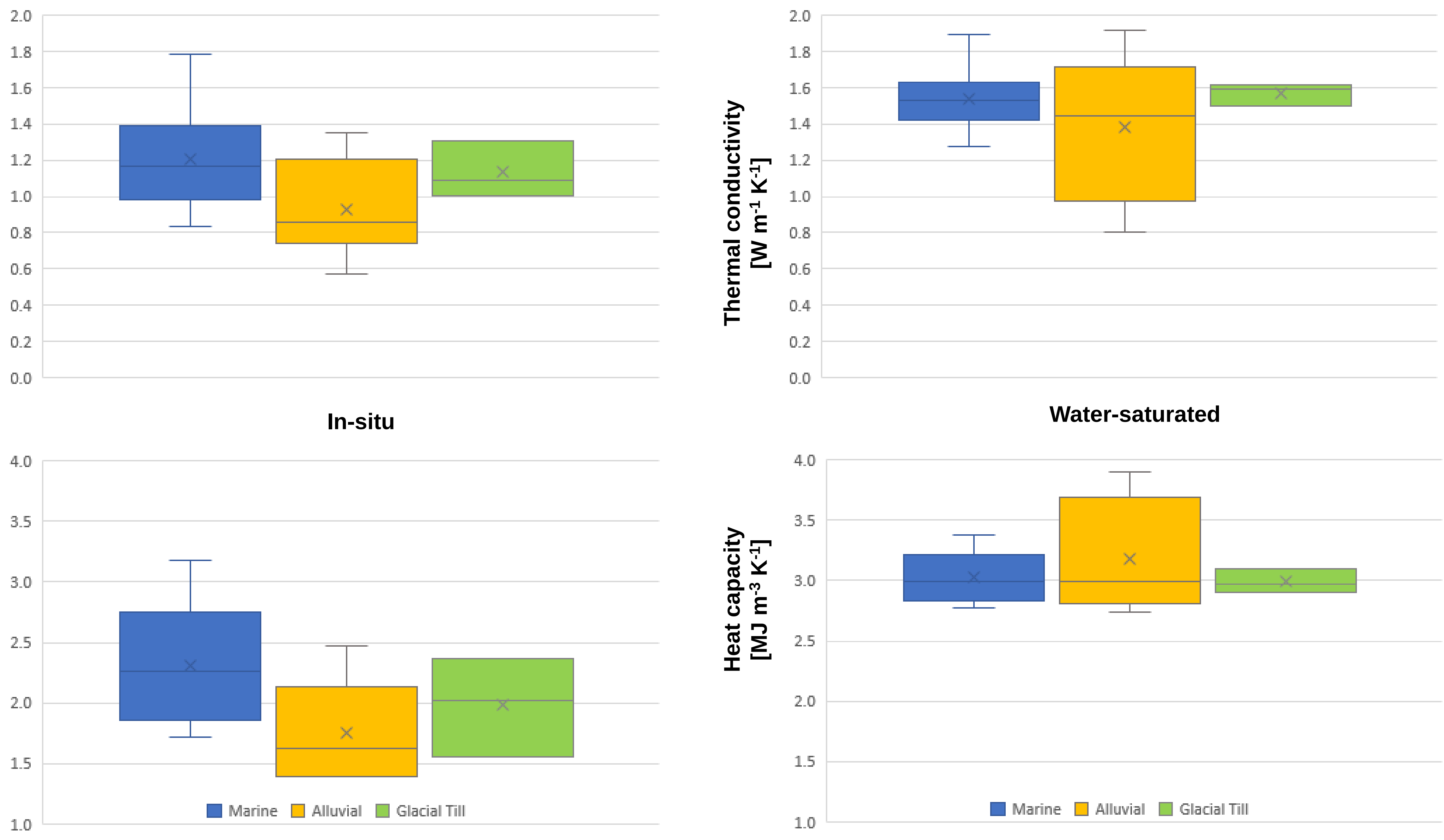
Methodology

Advance laboratory testing

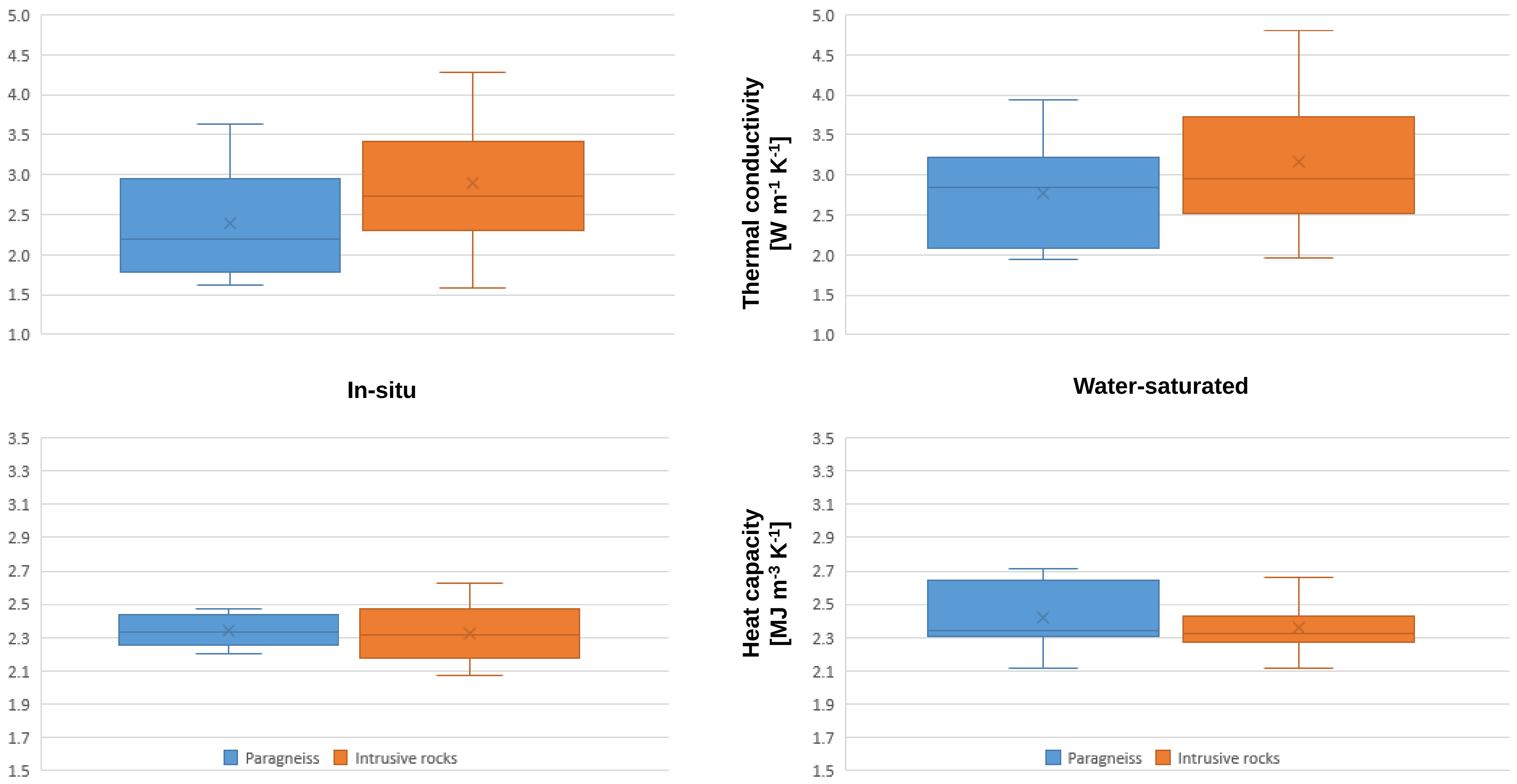
- Influence of temperature on thermal conductivity from permafrost to reservoir conditions (-10 to 180ºC; guarded heat flow meter)
- Influence of heterogeneity on thermal conductivity distribution (infrared scanner)
- Influence of pressure on porosity and permeability (10,000 psi; gas porosimeter and permeameter)



Thermal properties analysis – Quaternary sediments

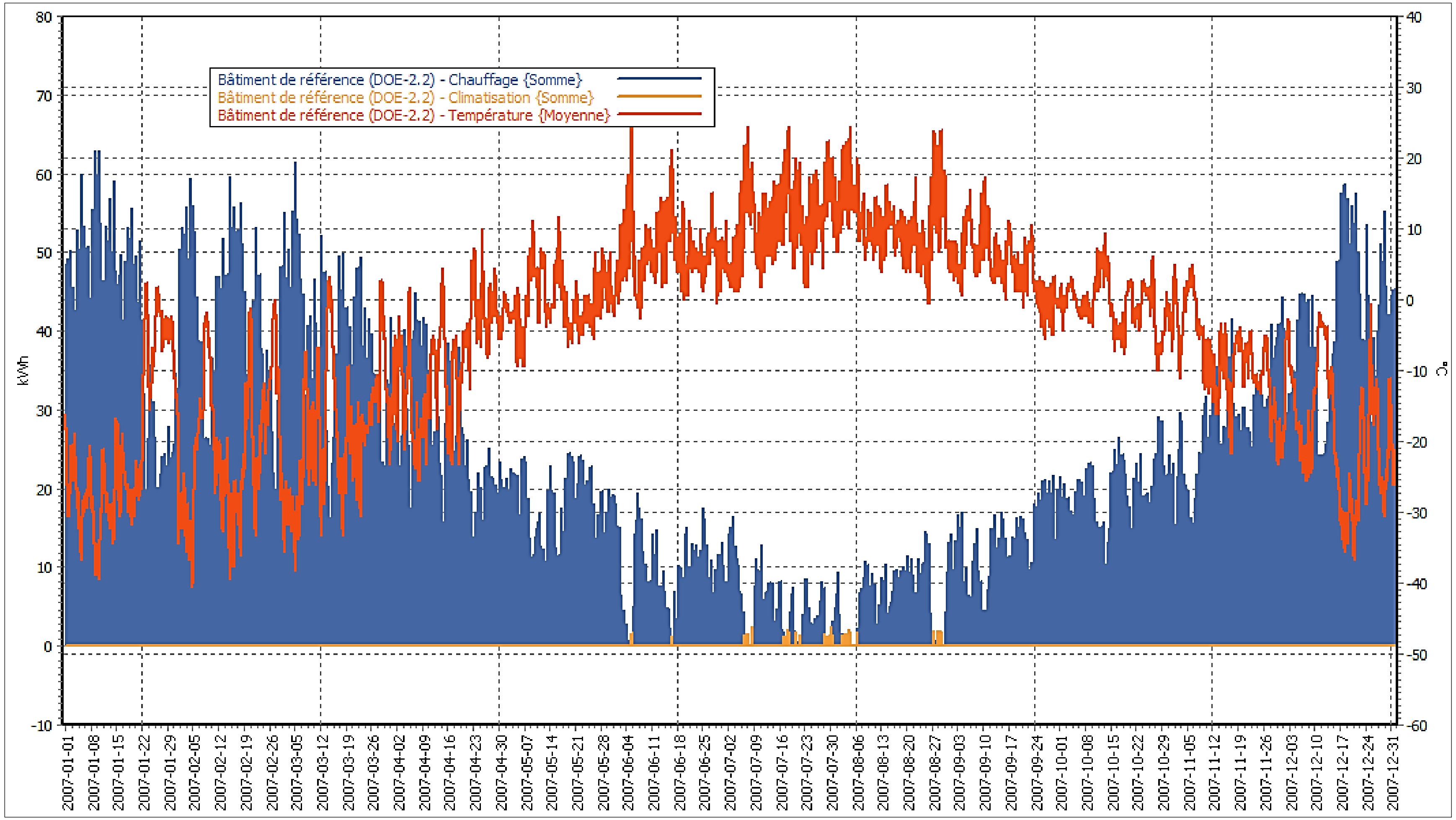


Thermal properties analysis – Rocks



Builiding and GSHP system simulations

SIMEB – GLHEPRO



Energy needs

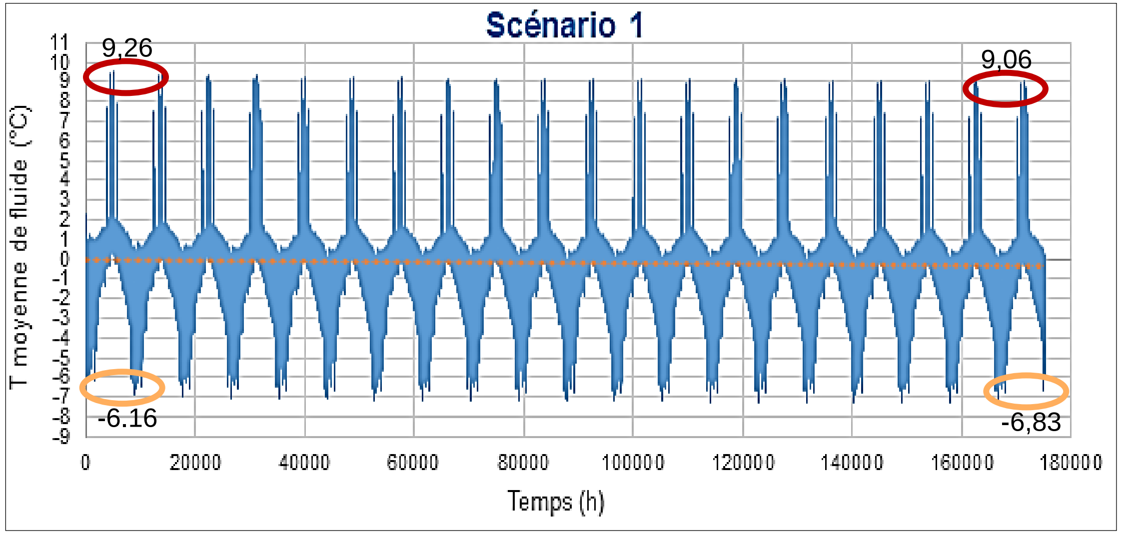
- 88 023 kWh/y heating
- 97 kWh/y cooling
- Highly unbalanced

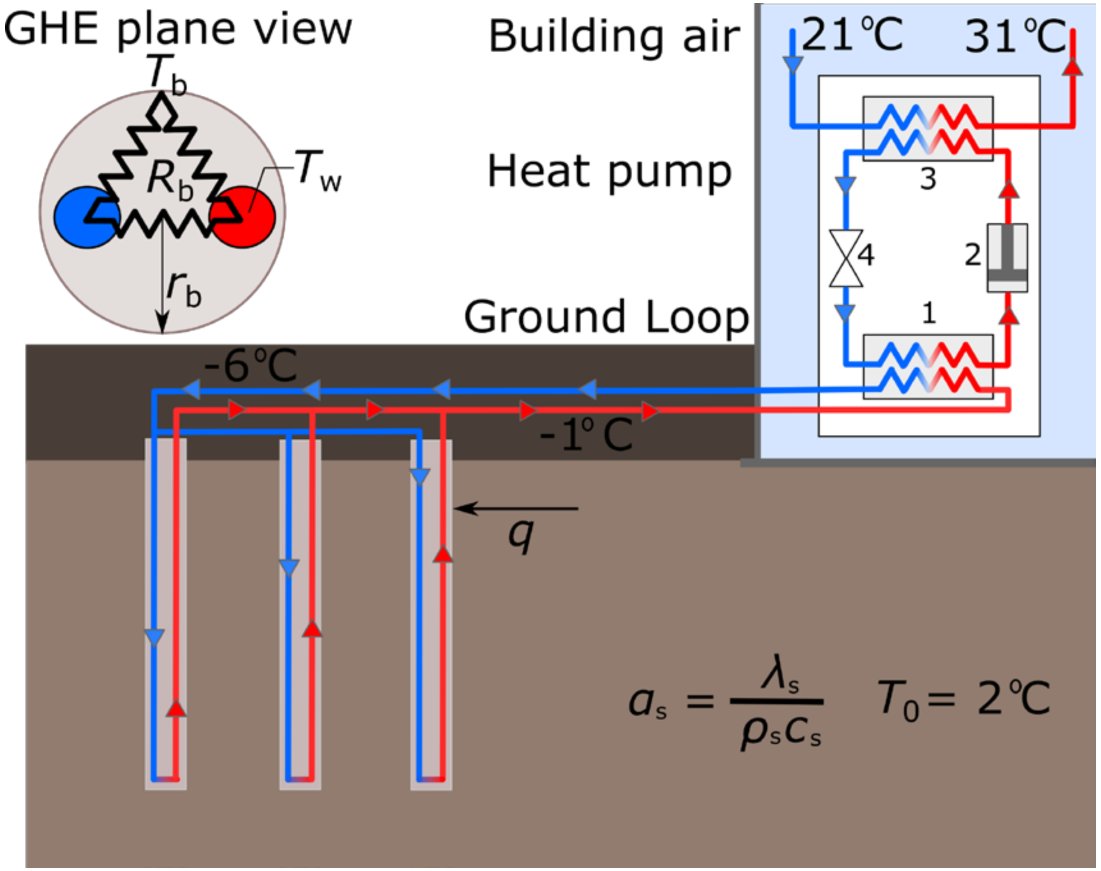
Builiding and GSHP system simulations

SIMEB – GLHEPRO

Geothermal heat pump system

- 200 m borehole length X 4
- 2.1 ºC average ground temperature
- 2.8 W/mK thermal conductivity
- 1.5 W/mK thermal conductivity
- 2.5 MJ/m³K heat capacity

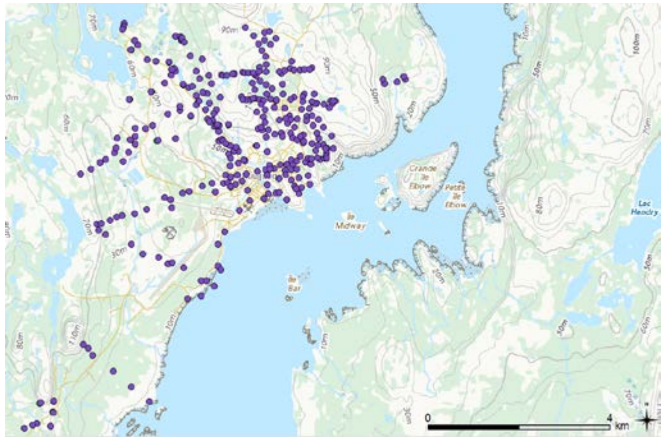




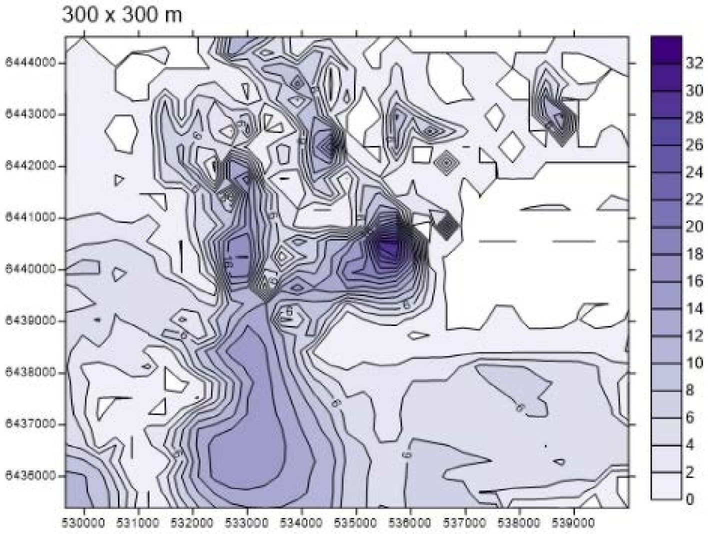
Geothermal heat pump potential mapping - G.POT approach

Depth of quaternary sediments in Kuujjuaq

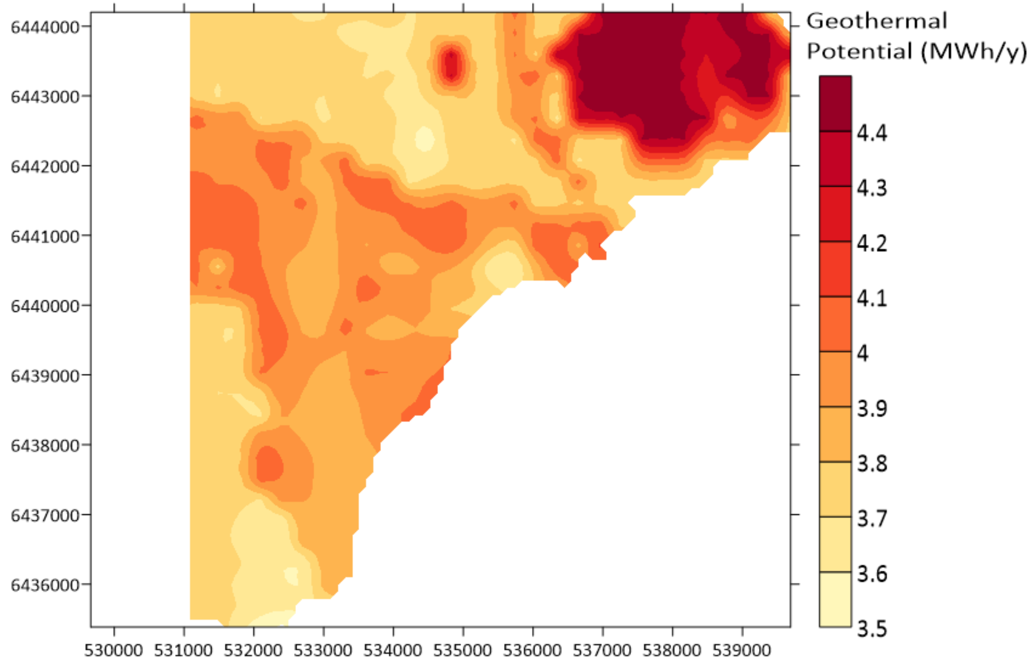
Measurements



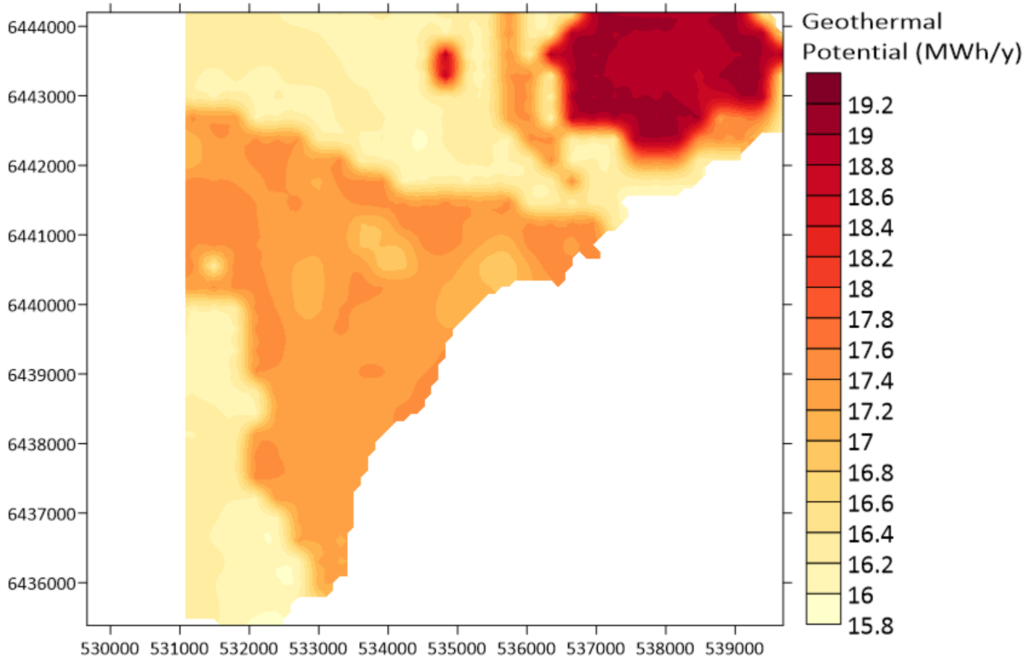
Interpolation



Borehole depth 100m



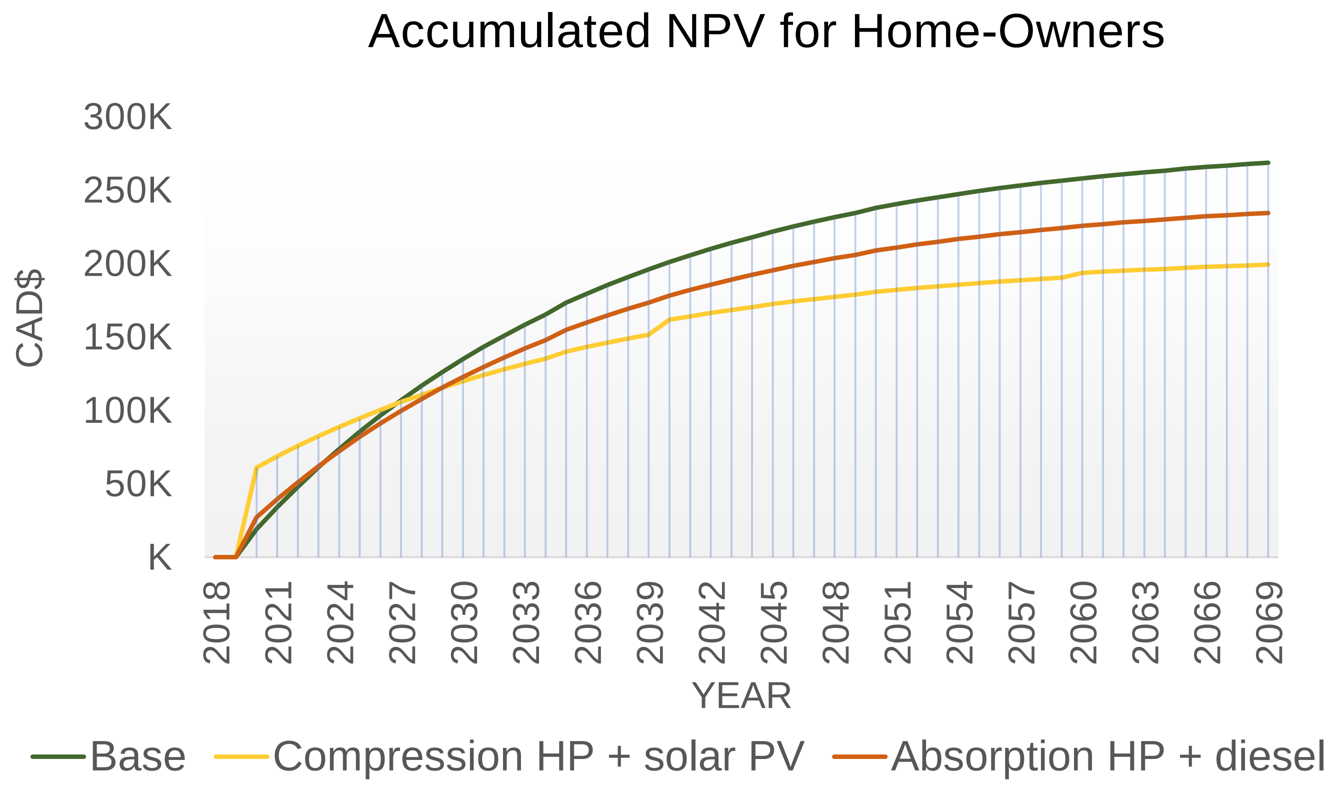
Borehole depth 300m



Life-cycle cost analysis – Net present value (NPV)

Heating scenario (71 kWh/y):

1) Non-renewable; business-as-usual (diesel boiler)
2) 100% renewable; compression heat pump with electricity input from solar PV panels
3) Partially renewable; absorption heat pump with thermal input from diesel



Government's NPV = $8,231.76

Government's NPV = $9,026.42

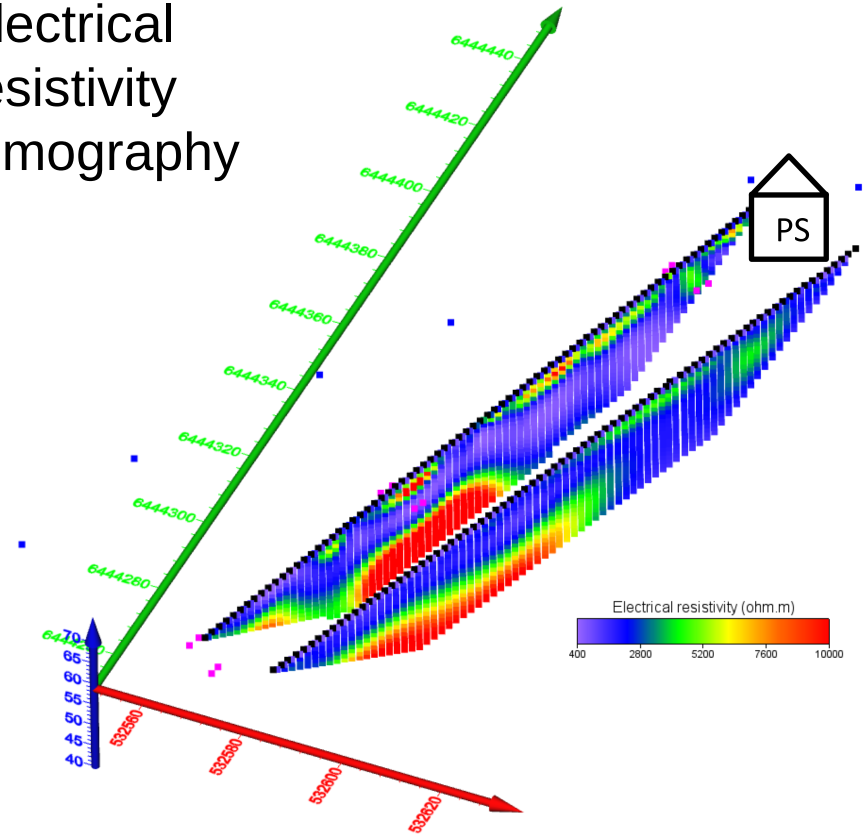
Government's NPV = $40,891.82

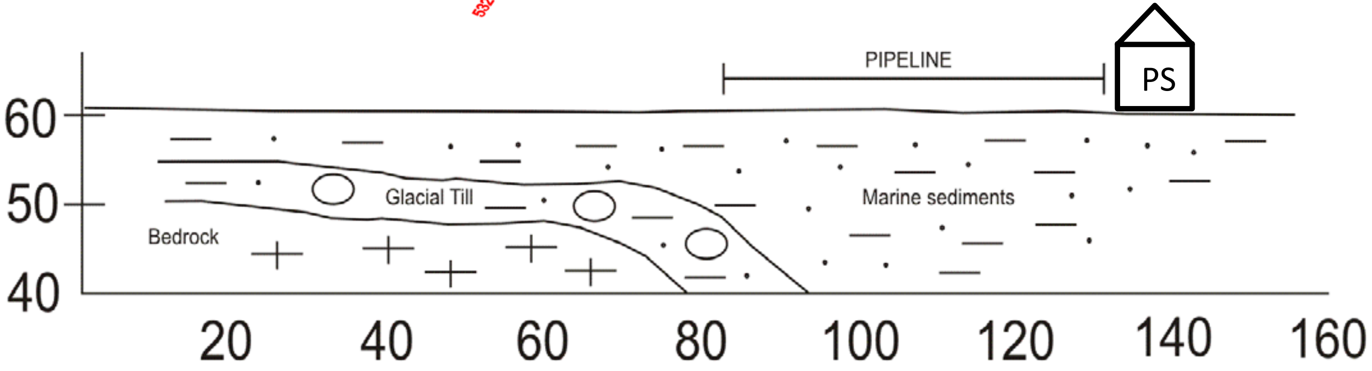
Government scheme:

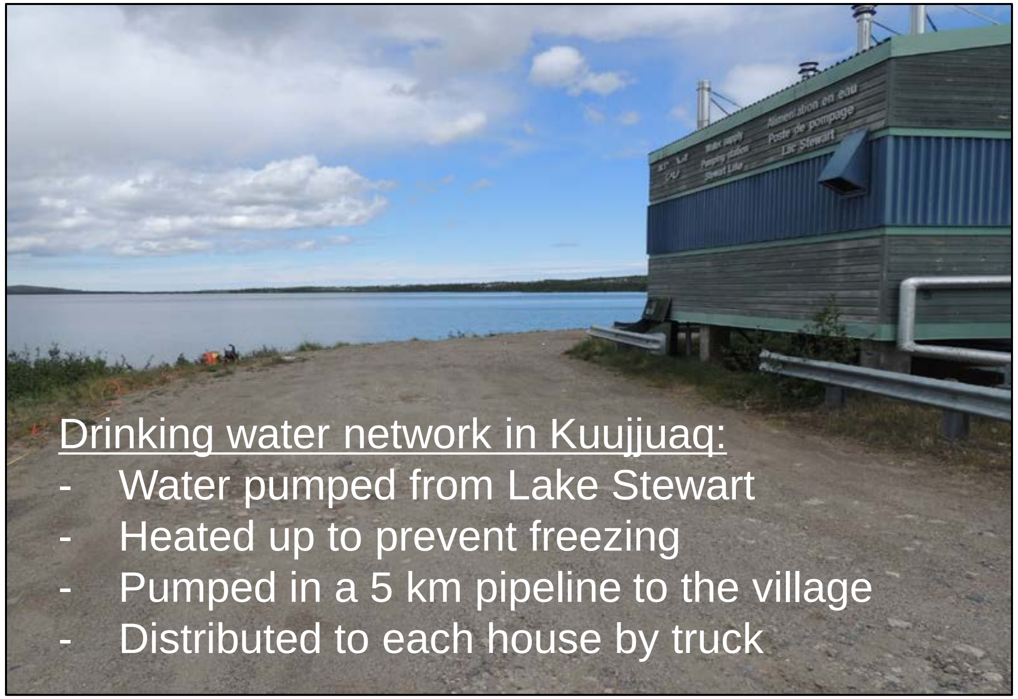
1) Government pays for 50% of heat pump and solar PV panels costs
2) No subsidy on diesel and electricity
3) Government supports drilling industry with cost of drilling $50/m
4) 19.4 $/tonne of CO_2

TES for Kuujjuaq pumping water station

Electrical resistivity tomography



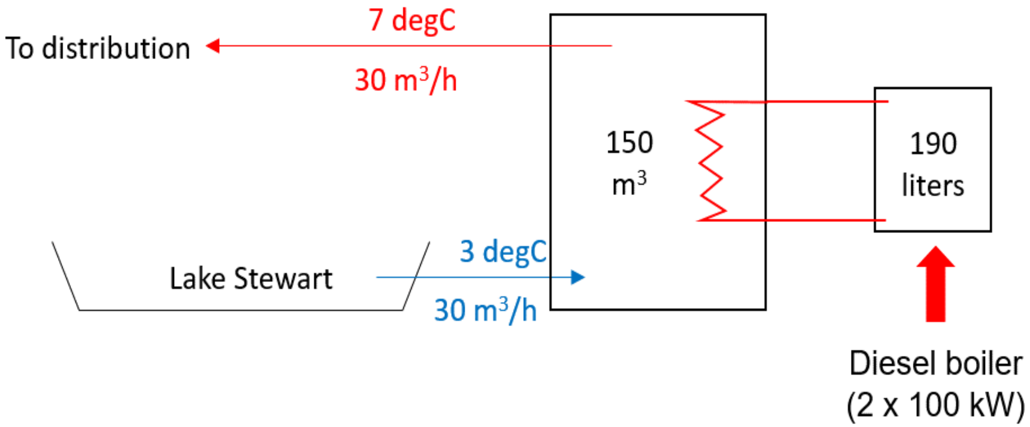




Drinking water network in Kuujjuaq:

- Water pumped from Lake Stewart
- Heated up to prevent freezing
- Pumped in a 5 km pipeline to the village
- Distributed to each house by truck

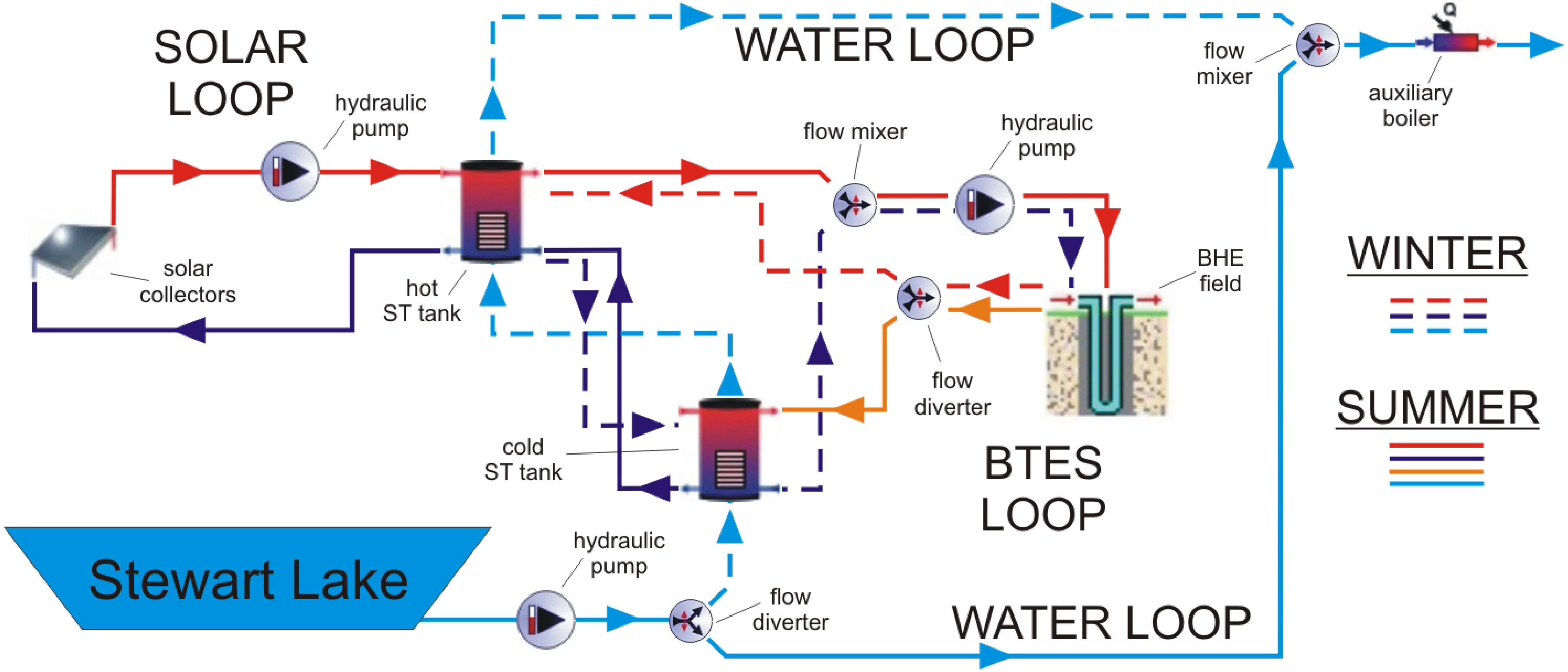
Existing plant



Energy consumption 570 MWh/y

Cost 113,000 $/y (diesel 2.1 $/l)

Pumping station - TES hypothesis



Pumping station - TES hypothesis

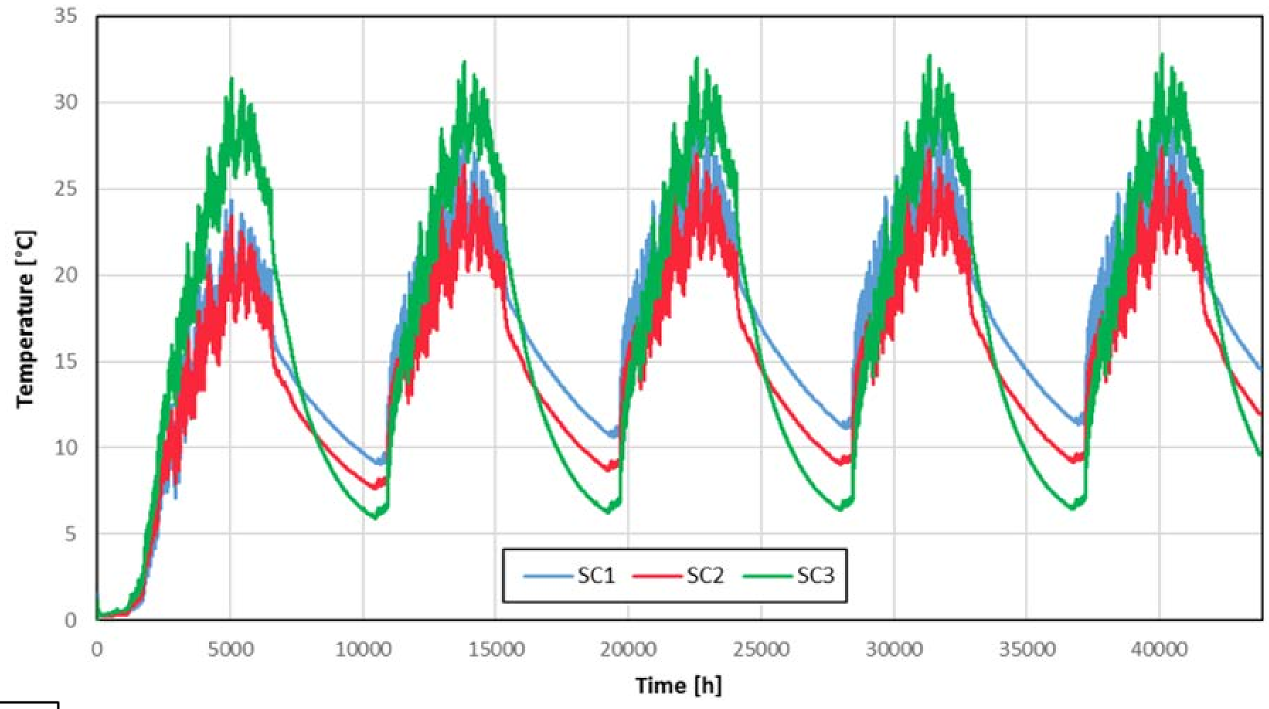
<u>SC1 base case</u>

- Solar area 1000 m^2
- One 100 m^3 short-term tank
- BTES volume of 22,000 m^3 with 100 BHE (30 m deep, spacing 3 m)
- Water with 50% propylene glycol

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11
Number of BHE (-)	100	100	100	100	100	50	50	100	150	100	100
Gross solar area (m^2)	1000	1000	1000	1000	1000	1000	1000	1500	1500	1000	1000
Number of STST (-)	1	2	2	2	2	2	2	2	2	2	2
BTES volume (m^3)	22,000	22,000	9500	22,000	22,000	9500	22,000	22,000	35,000	22,000	22,000
BHE spacing (m)	2.9	2.9	1.9	2.9	2.9	2.7	4.1	3	3	3	3
Shape factor (-)	1	1	1.5	1	1	1.5	1	1	0.8	1	1
Use of cold STST (-)	-	CHR/DIS	CHR/DIS	DIS	CHR/DIS	CHR/DIS	CHR/DIS	CHR/DIS	CHR/DIS	CHR/DIS	CHR/DIS
Pre-heating period (y)	0	0	0	0	1	0	0	0	0	0	0
Preheating *T* (°C)	-	-	-	-	10	-	-	-	-	-	-
Glycol in HCF (% vol.)	50	50	50	50	50	50	50	50	50	25	50
Flow rate in BTES (m^3/h)	40	40	40	40	40	40	40	40	60	40	60
Reynolds number in BHE (-)	1400	1400	1400	1400	1400	2800	2800	1400	1400	4400	2100

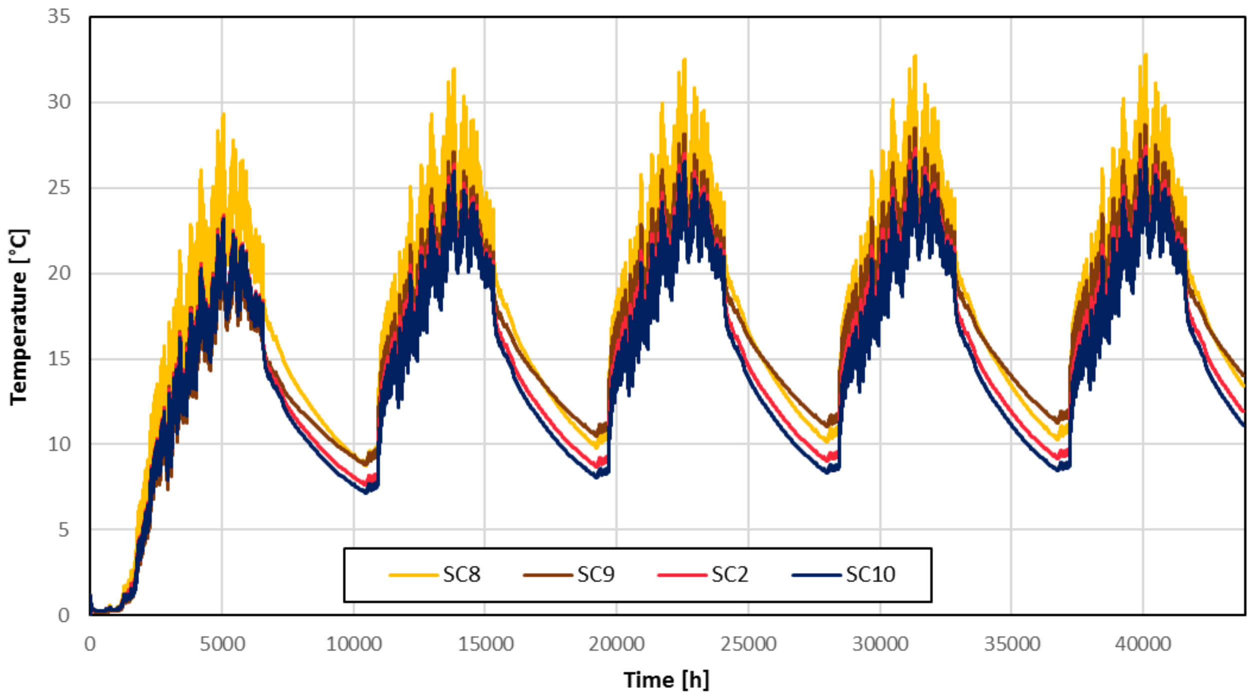
- SC2 has 2 short-term storage tanks
- SC3 has half the BTES volume
- SC4 the cold tank is used in discharge phase only
- SC5 has a pre-heating period to 10°
- SC6 and SC7 less BHEs to save on drilling activities
- SC8 and SC9 bigger solar area
- SC10 and SC11 higher Reynolds number

TES simulations - TRNSYS



Temperature in the BTES center
(5 years simulation)

- SC2 lowers the BTES temperature by 2 ºC compared to SC1 due to the second short-term tank
- SC3 has the maximum T span dues to its small volume

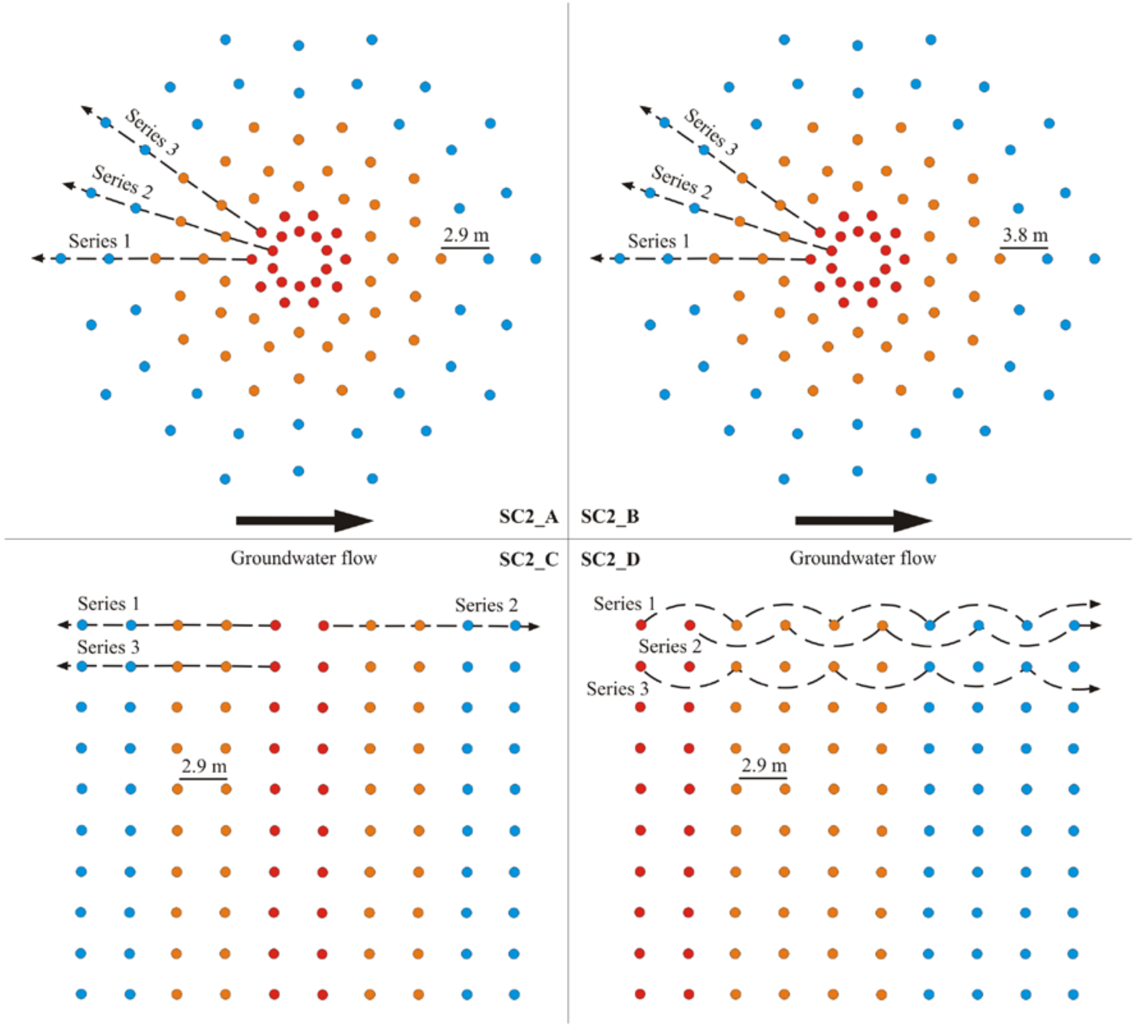


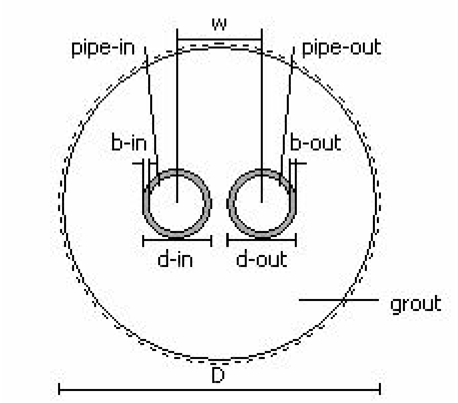
- SC9 lowers the BTES temperature less than SC2 because of the bigger volume
- SC10 works slightly better than SC2 due to turbulent flow in BHEs
- EQUILIBRIUM after 3-4 years

TES simulations - FEFLOW

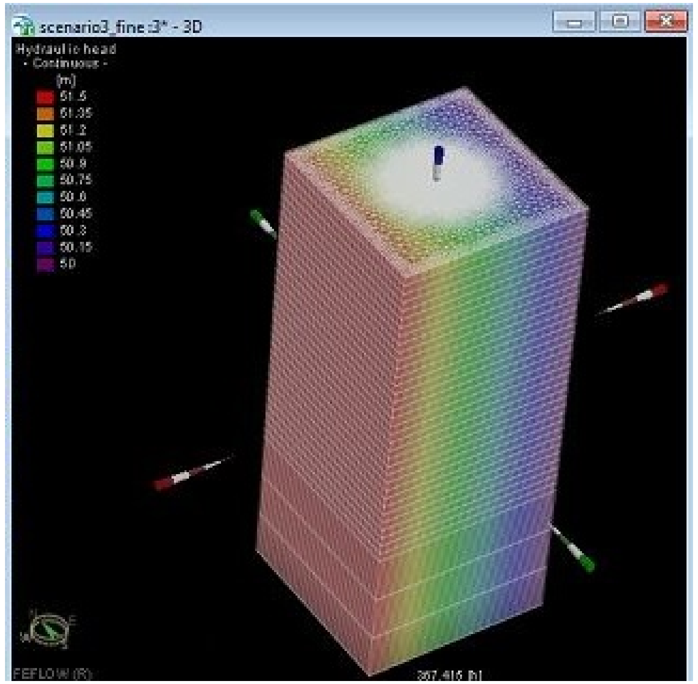
- Single-U pipes
- Water glycol 50%
- 3D model 100 x 100 x 50 m
- Mesh ~ 500,000 elements
- 16 months simulation
- (10 injection – 6 extraction)
- Thermal conductivity 1.5 W/mK
- Heat capacity 3 MJ/m^{3}K

- Initial T 0 degC
- Hydraulic grad. 1,5%
- Hydraulic cond. 5 x 10^{-5} m/s
- Thermal cond. 1.5 W/mK
- Heat cap. 3 MJ/m^{3}K



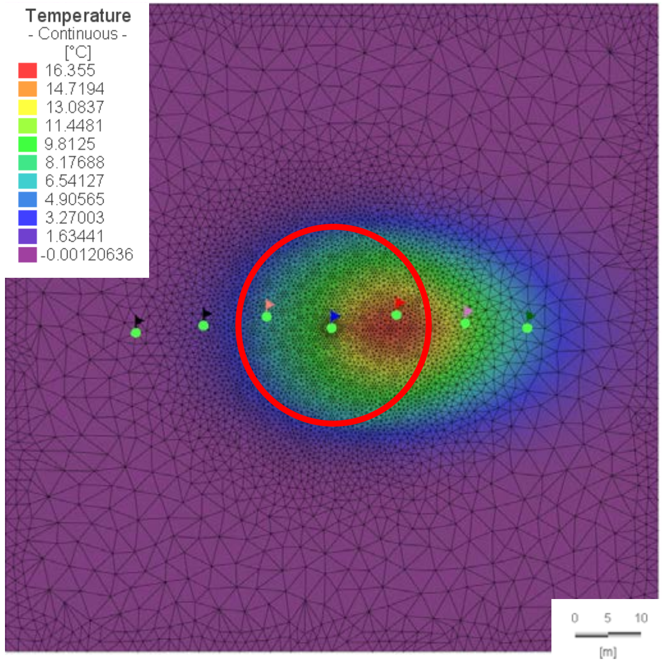


Computational method
(Eskilson & Claesson 1988)

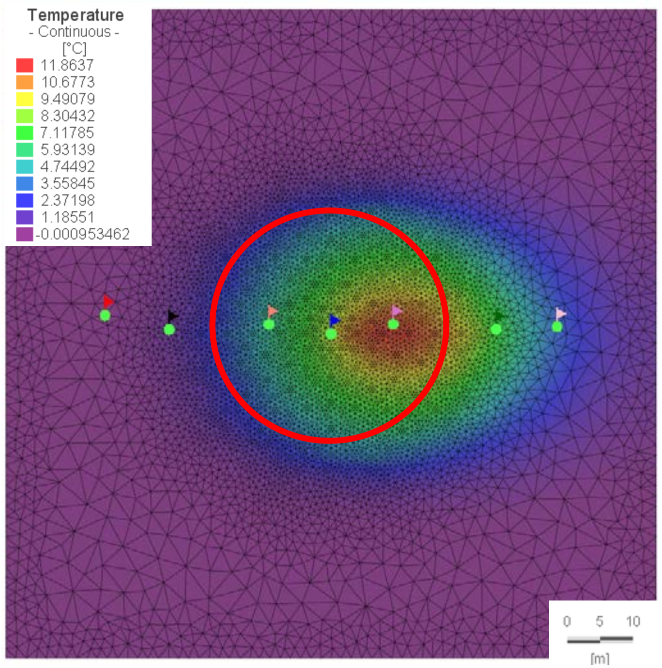


Numerical results - FEFLOW

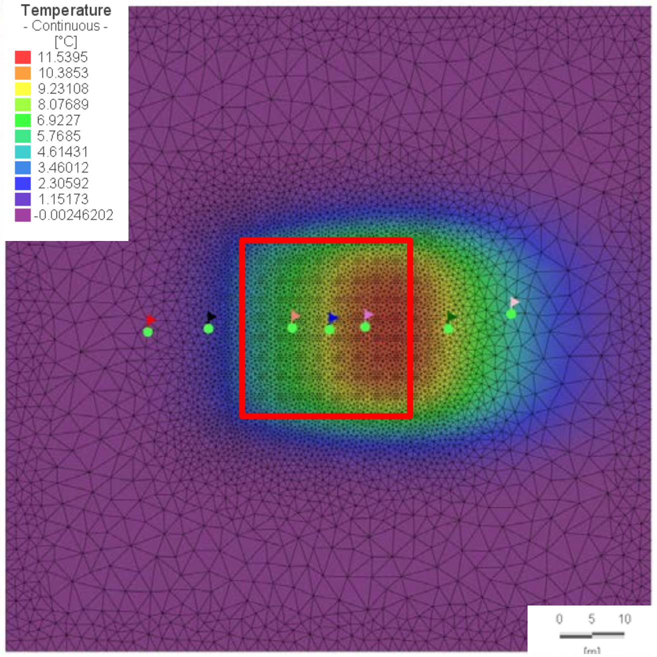
Scenario A



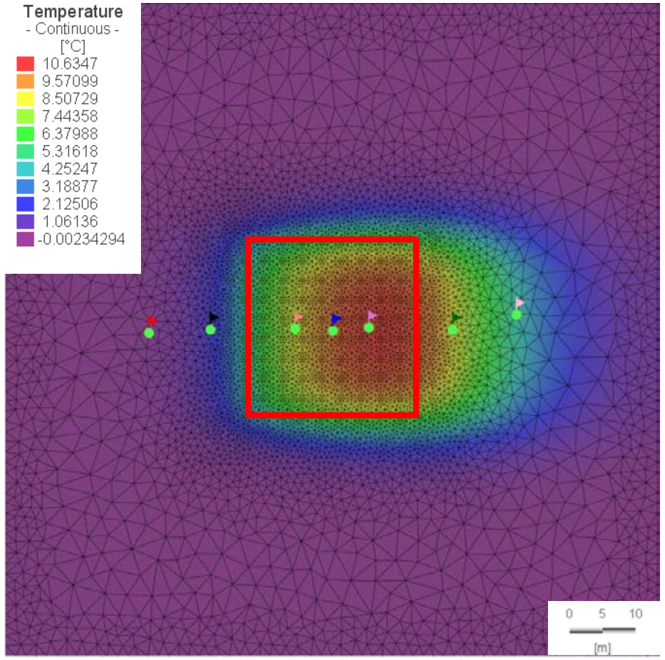
Scenario B



Scenario C



Scenario D



	SC2_A	SC2_B	SC2_C	SC2_D
Spacing [m]	2.9	3.8	2.9	2.9
Storage shape [-]	cylinder	cylinder	square	square
Radius / Half side [m]	15	20	15	15
Shape factor [-]	0.99	0.75	0.99	0.99
Storage volume [m^3]	22,000	38,000	22,000	22,000
BHE connection in CHR	C to B	C to B	C to B	downward
BHE connection in CHR	B to C	B to C	B to C	upward

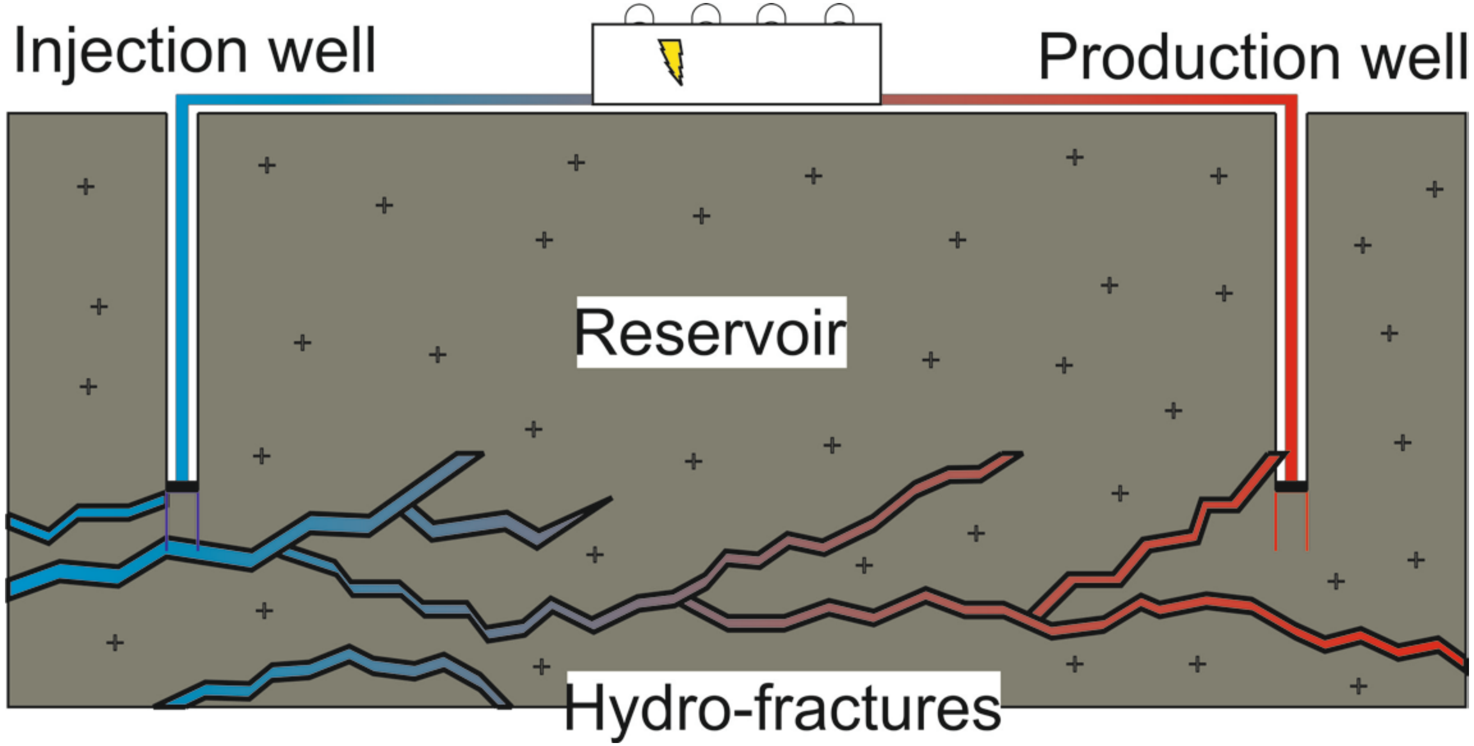
TES performance for drinking water supplies

Photo: J. Tukkiapik

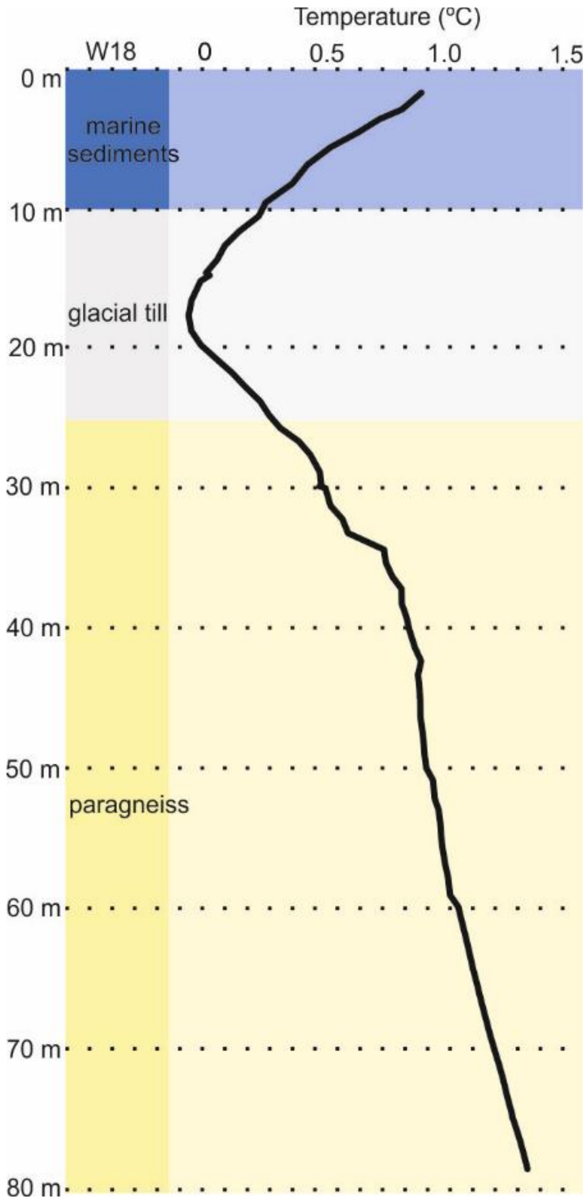
- BTES provided **45-50% of solar fraction**
- Equilibrium is reached after 3-4 years
- **Efficiency of 60%** can be achieved
- **10% additional heat losses** occur by **groundwater advection**
- **Unconventional BHE disposition** could help reducing the value to **5%** and retrieve more energy
- SC2 could help saving **32,000 $/y** and **45 tons of CO_2eq/y**

Are deep geothermal resources a viable alternative solution to produce heat for northern communities of Québec?

Enhanced Geothermal Systems



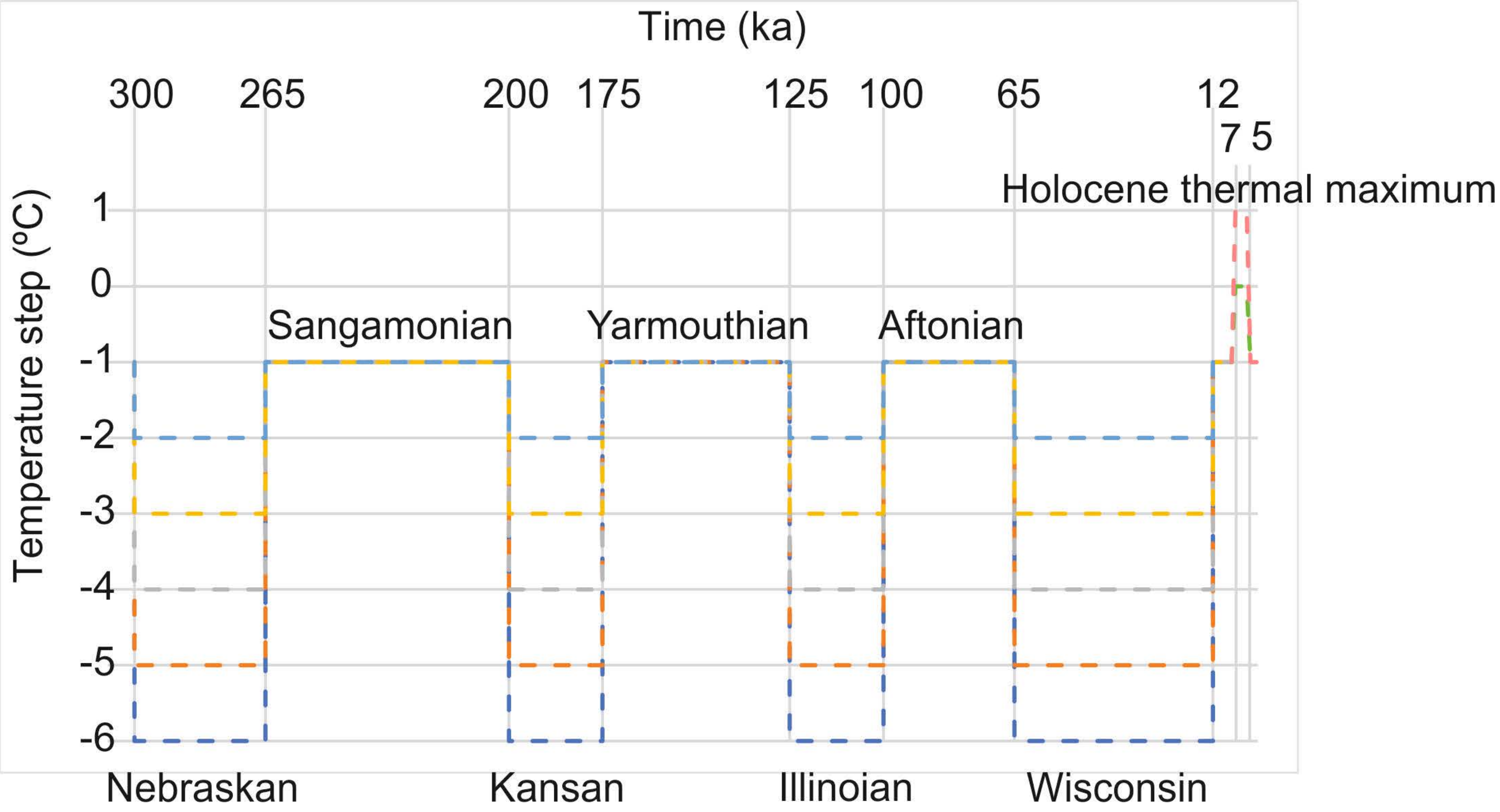
Temperature-depth profile



	Marine sediments	Glacial Till	Paragneiss
Thermal cond. ($W\ m^{-1}\ K^{-1}$)	1.2	1.1	2.4
Thermal dif. ($x10^{-6}\ m^2\ s^{-1}$)	0.046	0.050	1.018
Heat cap. ($MJ\ m^{-3}\ K^{-1}$)	2.3	2.0	2.4

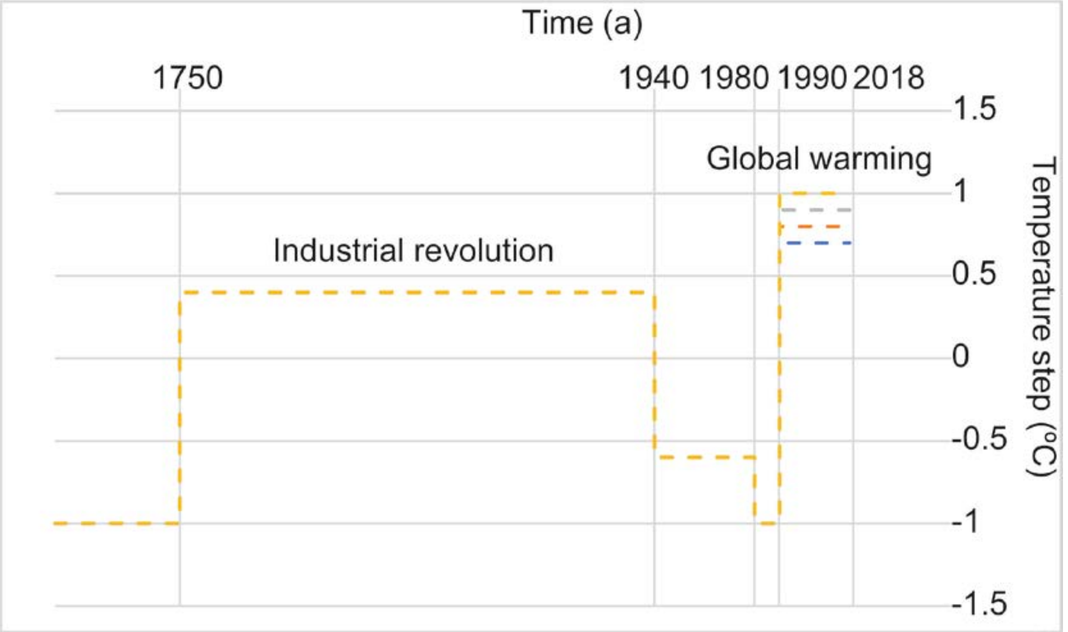
Paleoclimate corrections

Quaternary glaciations and Holocene thermal maximum

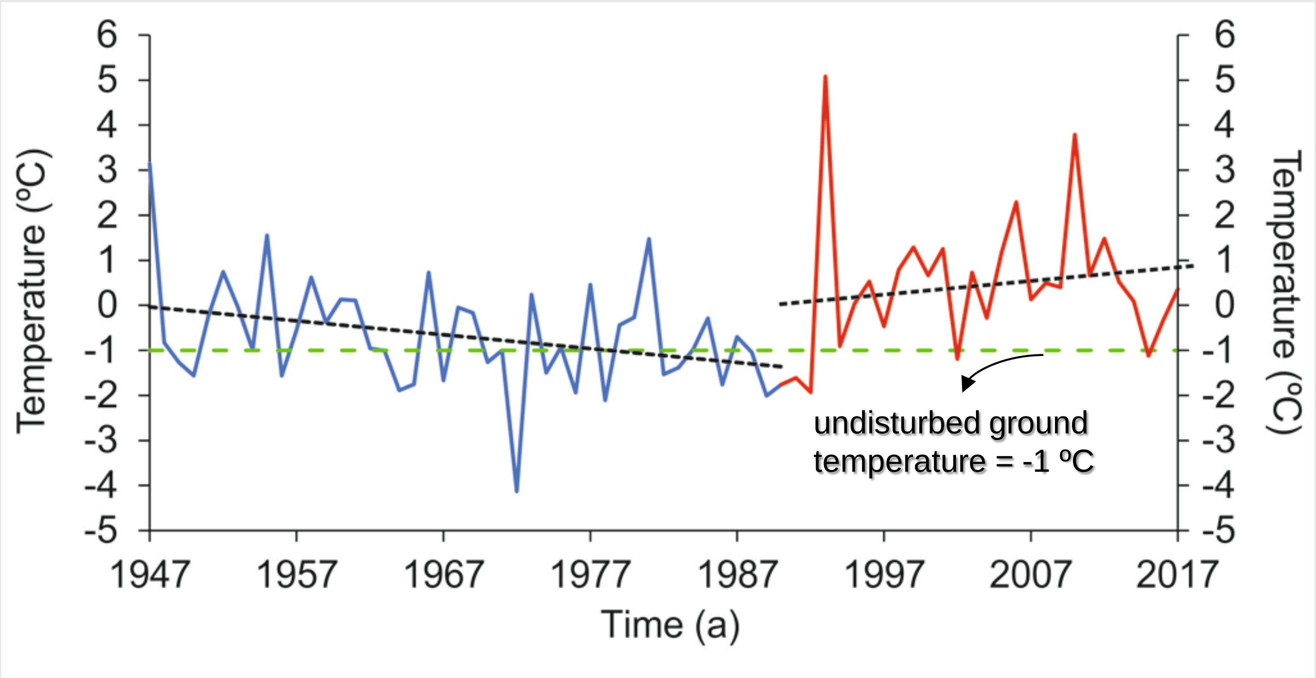


Paleoclimate corrections

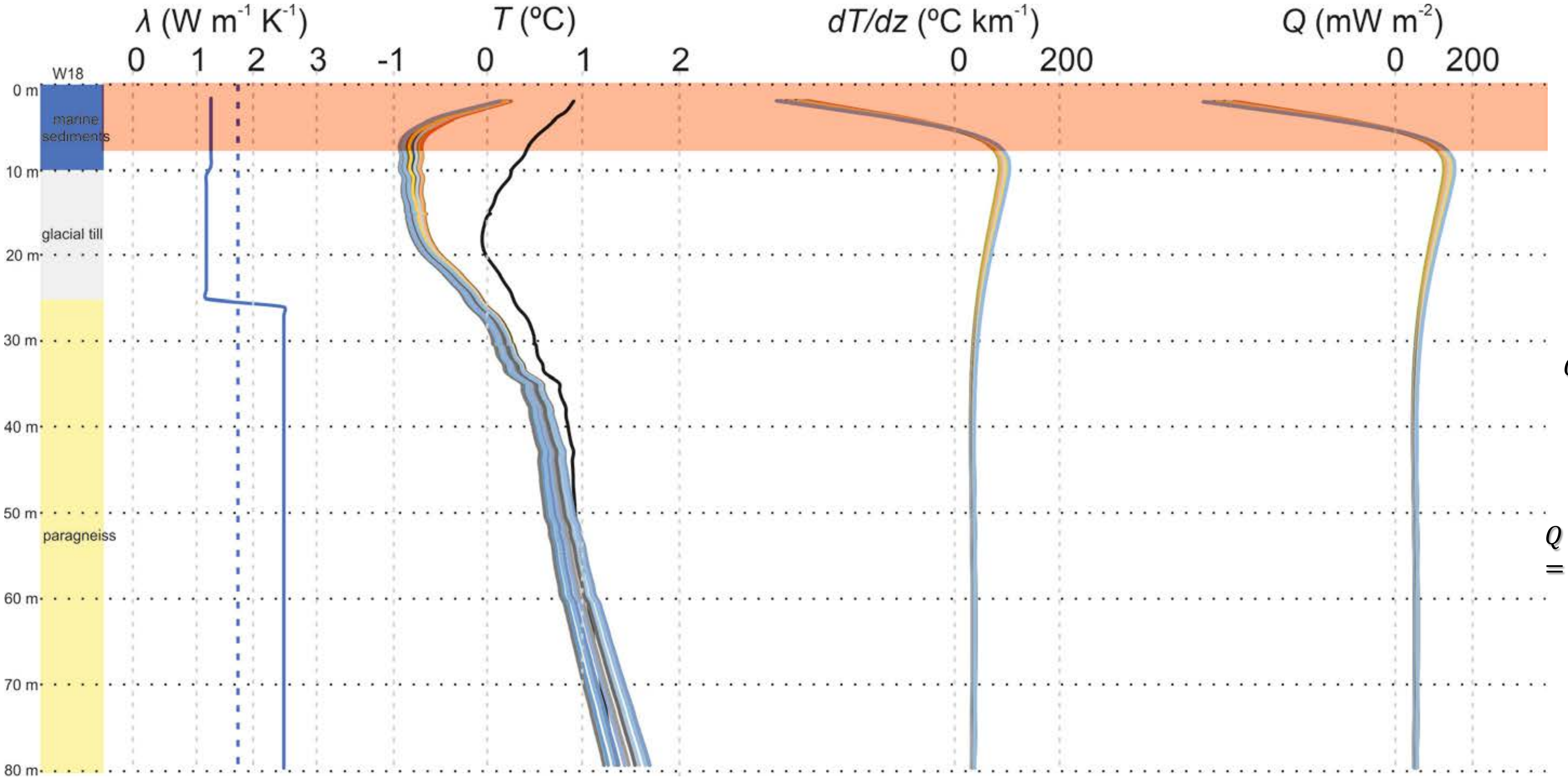
Recent events



annual average ground temperature based on surface air temperature records



Geothermal gradient & heat flow



$\overline{\lambda_{harmonic}} = 1.79\ \mathrm{W\ m^{-1} K^{-1}}$

$\frac{dT}{dz} = 19.9\ \mathrm{K\ km^{-1}}$

$\frac{dT}{dz} = [28.2 - 35]\ \mathrm{K\ km^{-1}}$

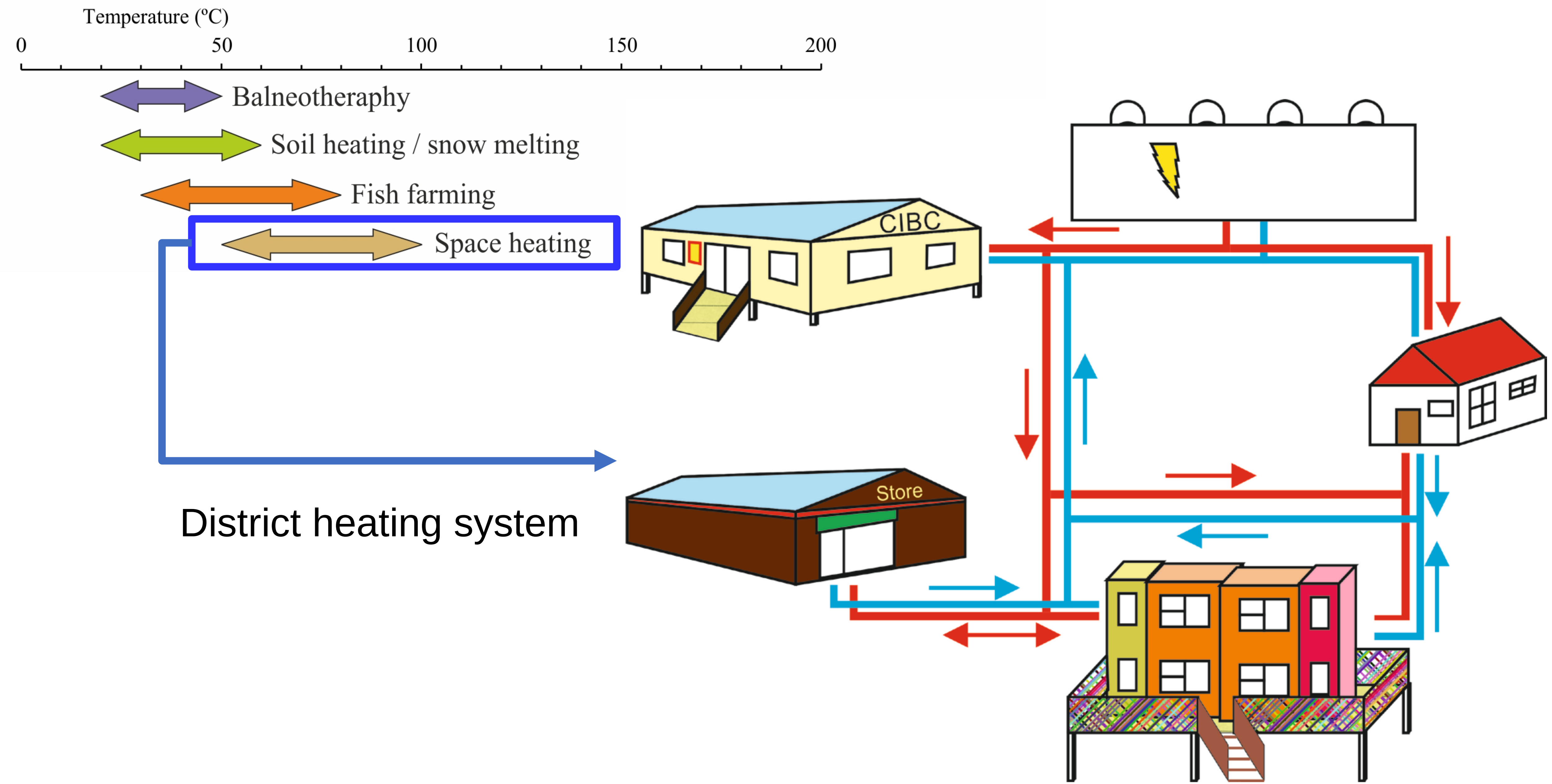
$Q = 35.6\ \mathrm{mW\ m^{-2}}$

$Q = [50.5\ - 62.7]\ \mathrm{mW\ m^{-2}}$

Paleoclimate correction avoid an underestimation of the geothermal gradient and surface heat flow

Increase of 29 to 43 %

Estimation of the temperature field at depth (2-5 km)



District heating system

Éléonore Mine – Gold Corp

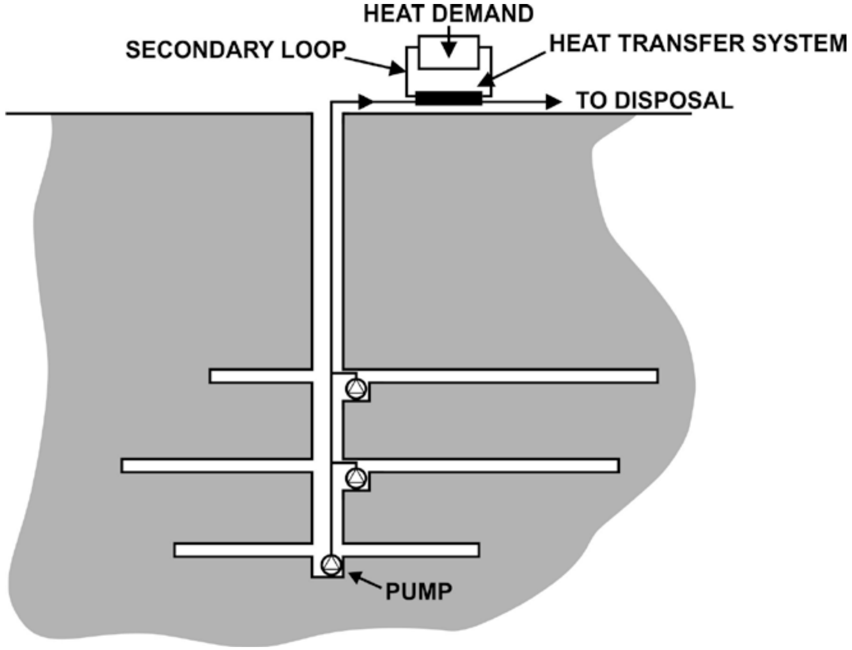
(Beausoleil, 2015)

High power demand for heating

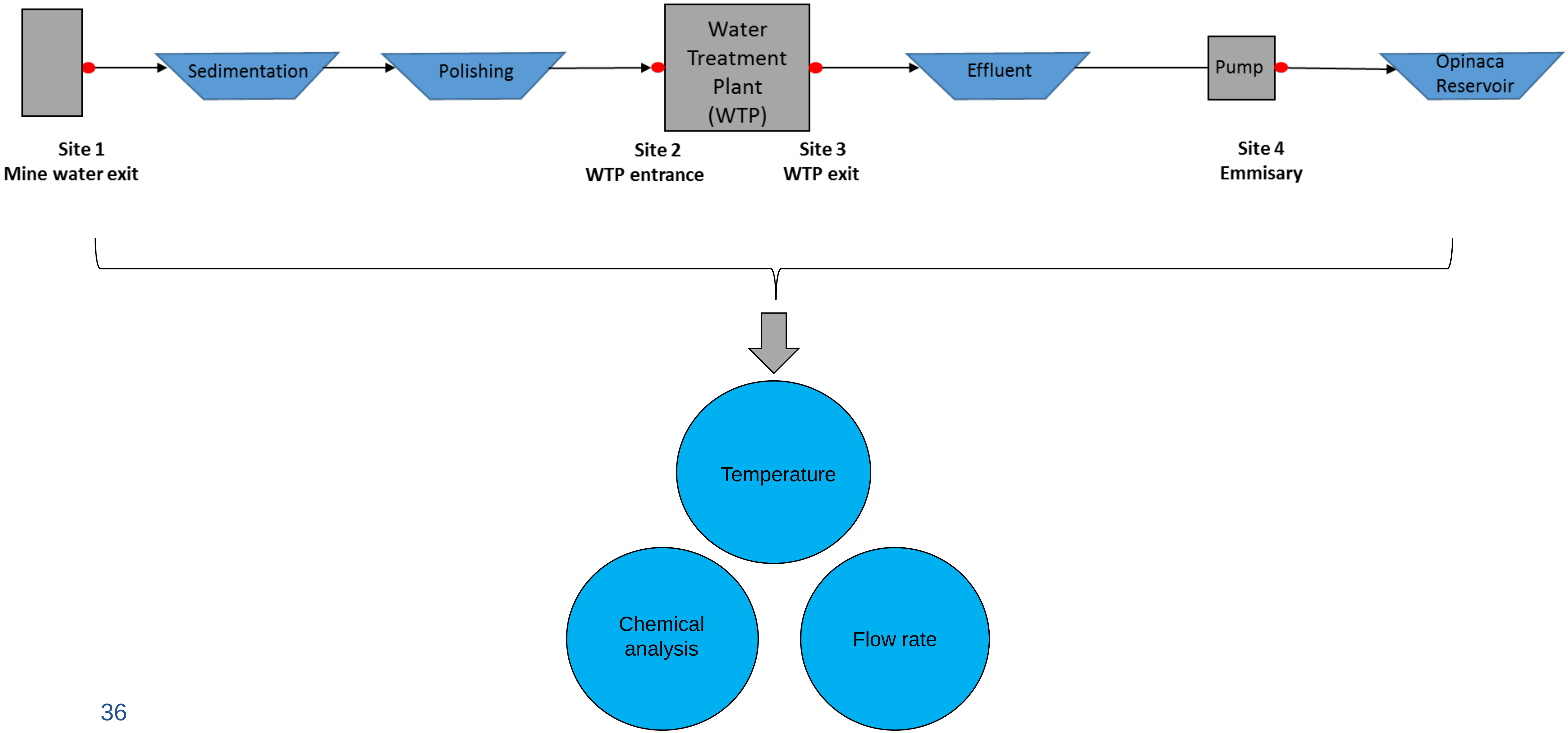
36 thermal MW needed to heat the underground workings

Environmental

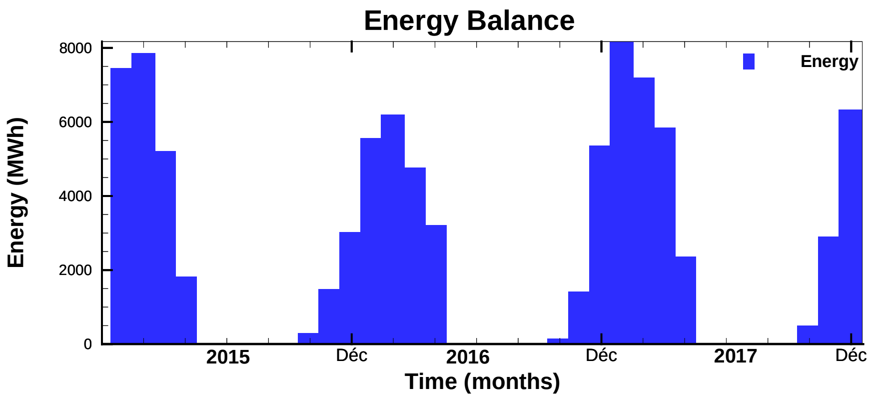
Propane burner system is used as heating source

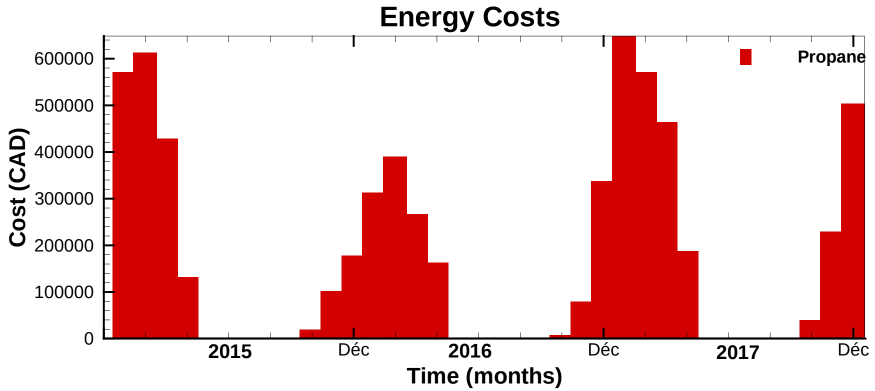


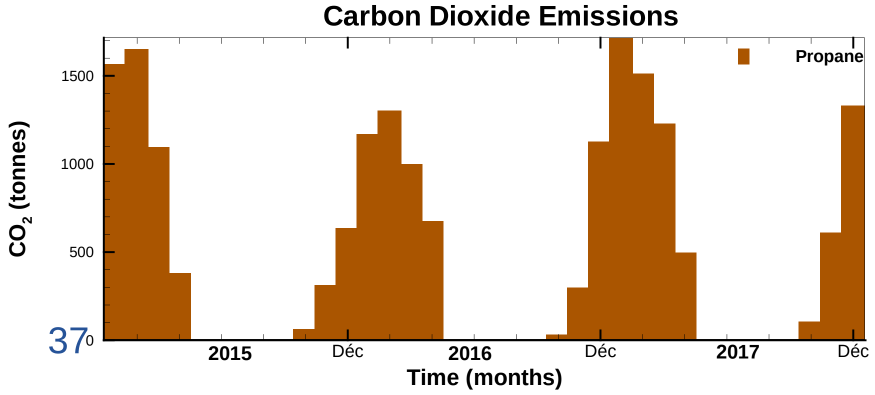
Mine water system and site evaluation



Energy assessment – base case







Energy

26.6 GWh/year needed to heat the underground workings

Economic

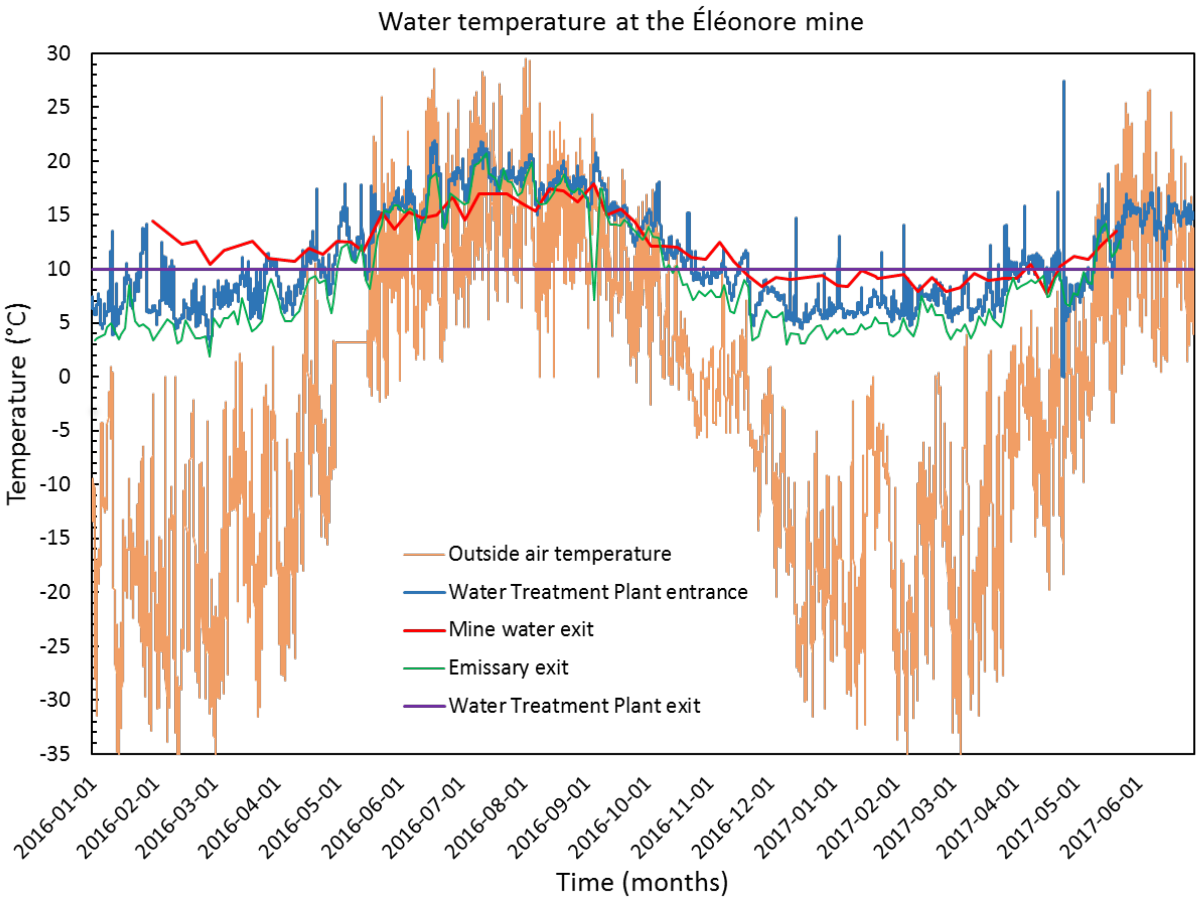
1.5 million $/year

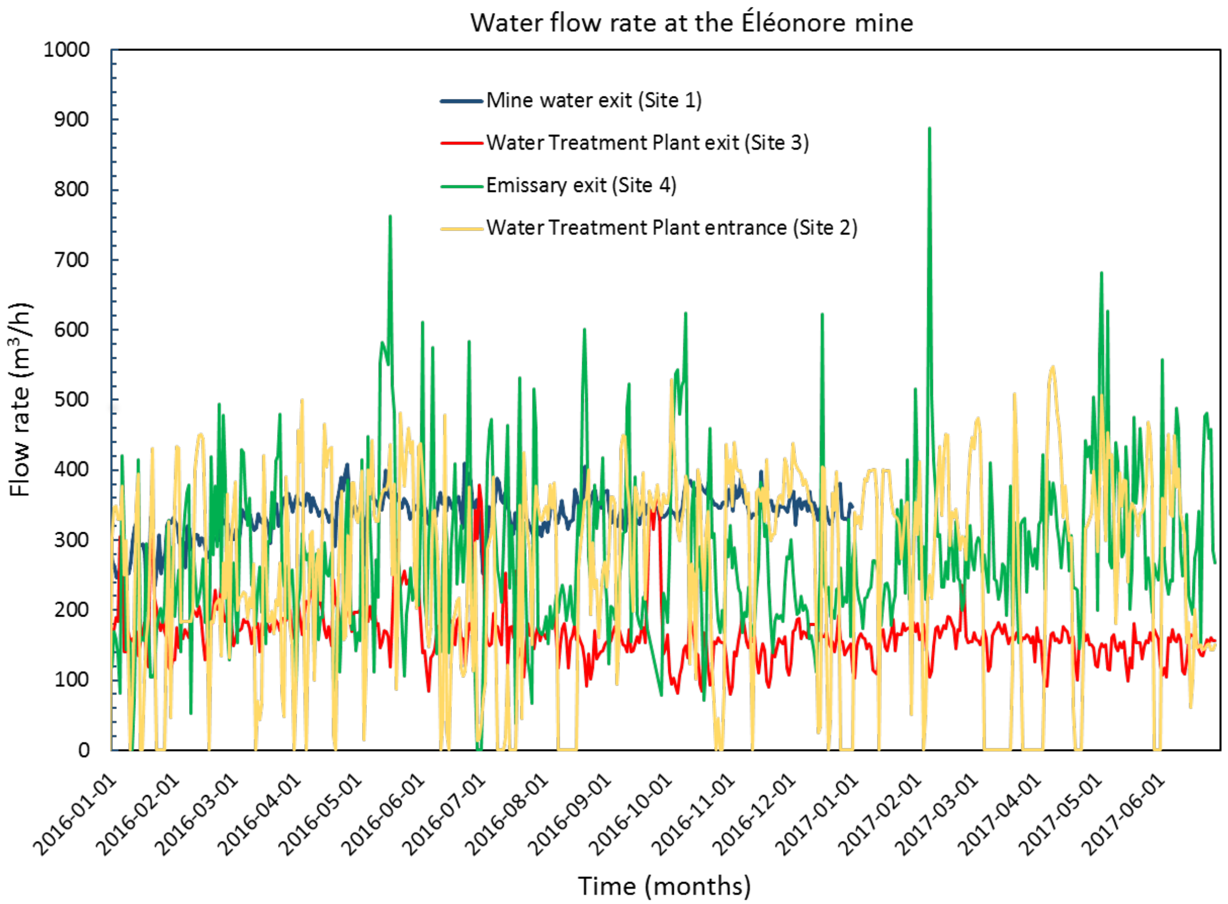
Environmental

5 600 tonnes of CO_2 annually

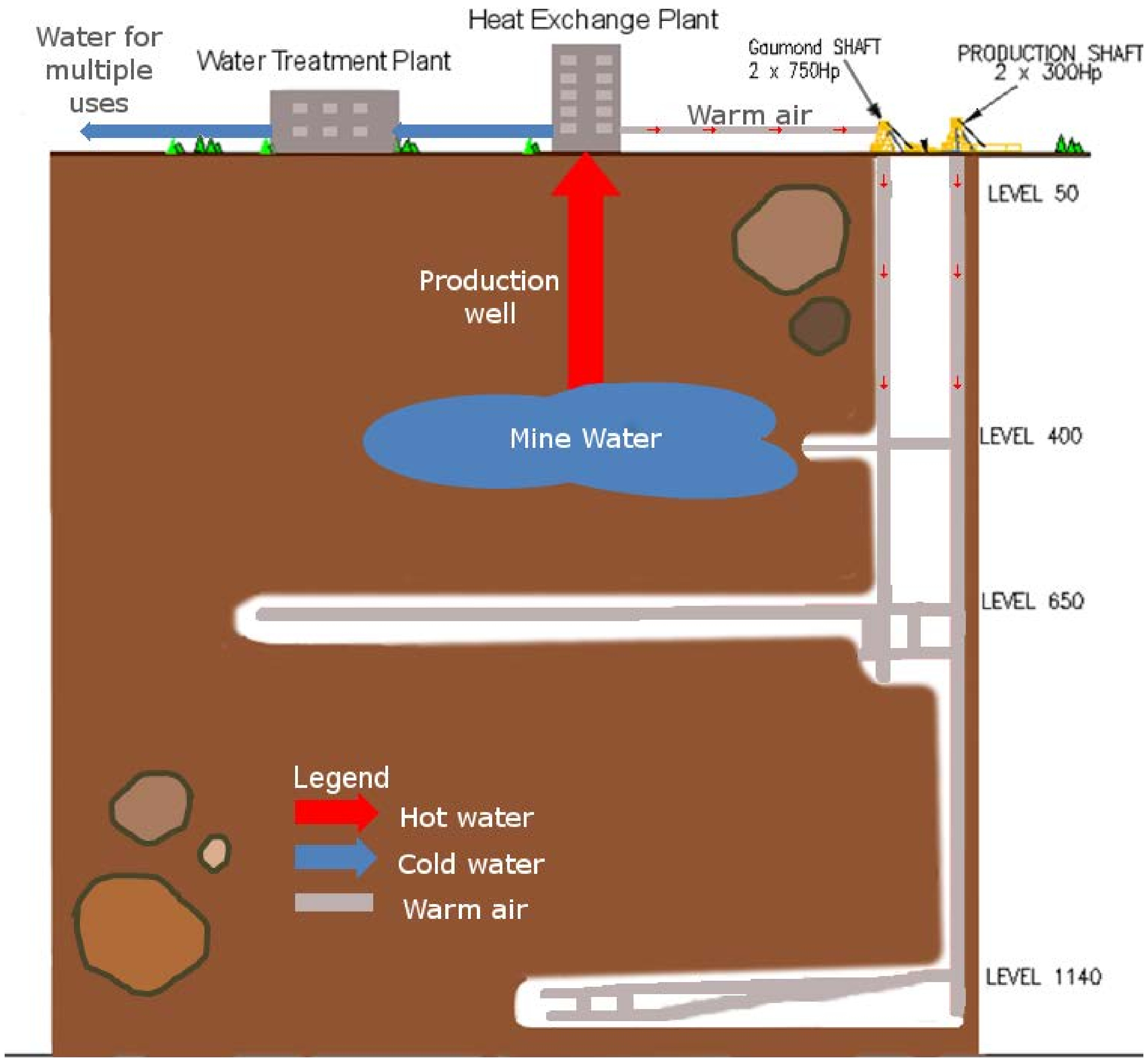
Flow rate and temperature

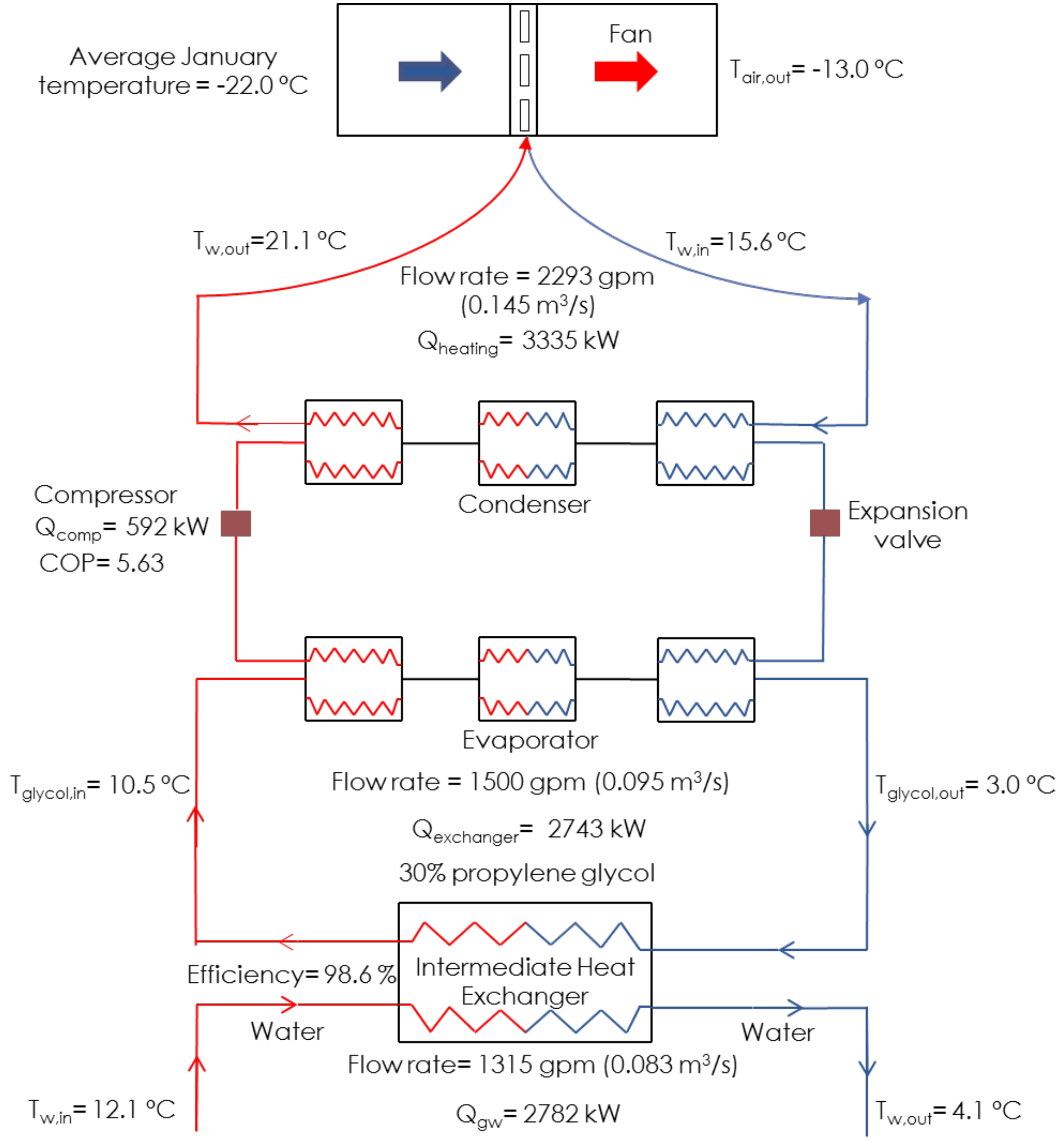
- Average water flow rate: 299 m^3/h (1316 gpm)
- Average water temperature: 12.2 ºC



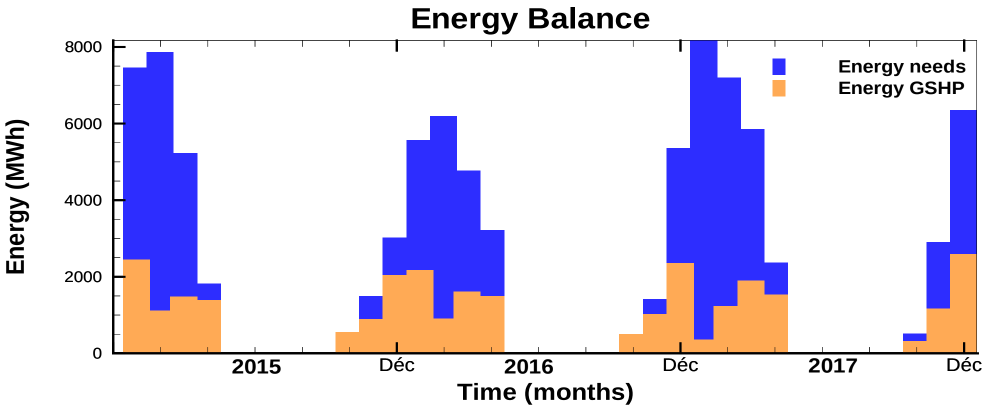


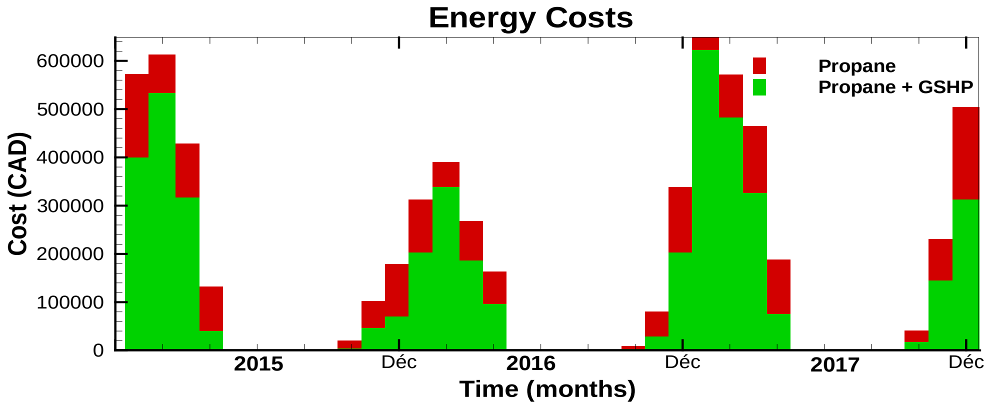
Geothermal heat pump system design

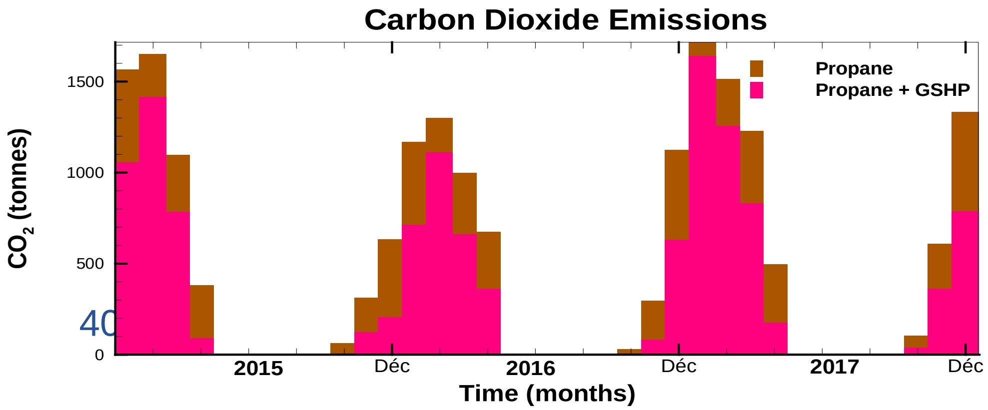




Energy assessment – heat pump







Energy

37 % of heating needs could be supplied by a geothermal heat pump system

Economic

$481K/year in savings

Environmental

CO_2 emission reduced by 2 037 tonnes/year

CANADA'S DIESEL DEPENDENT COMMUNITIES

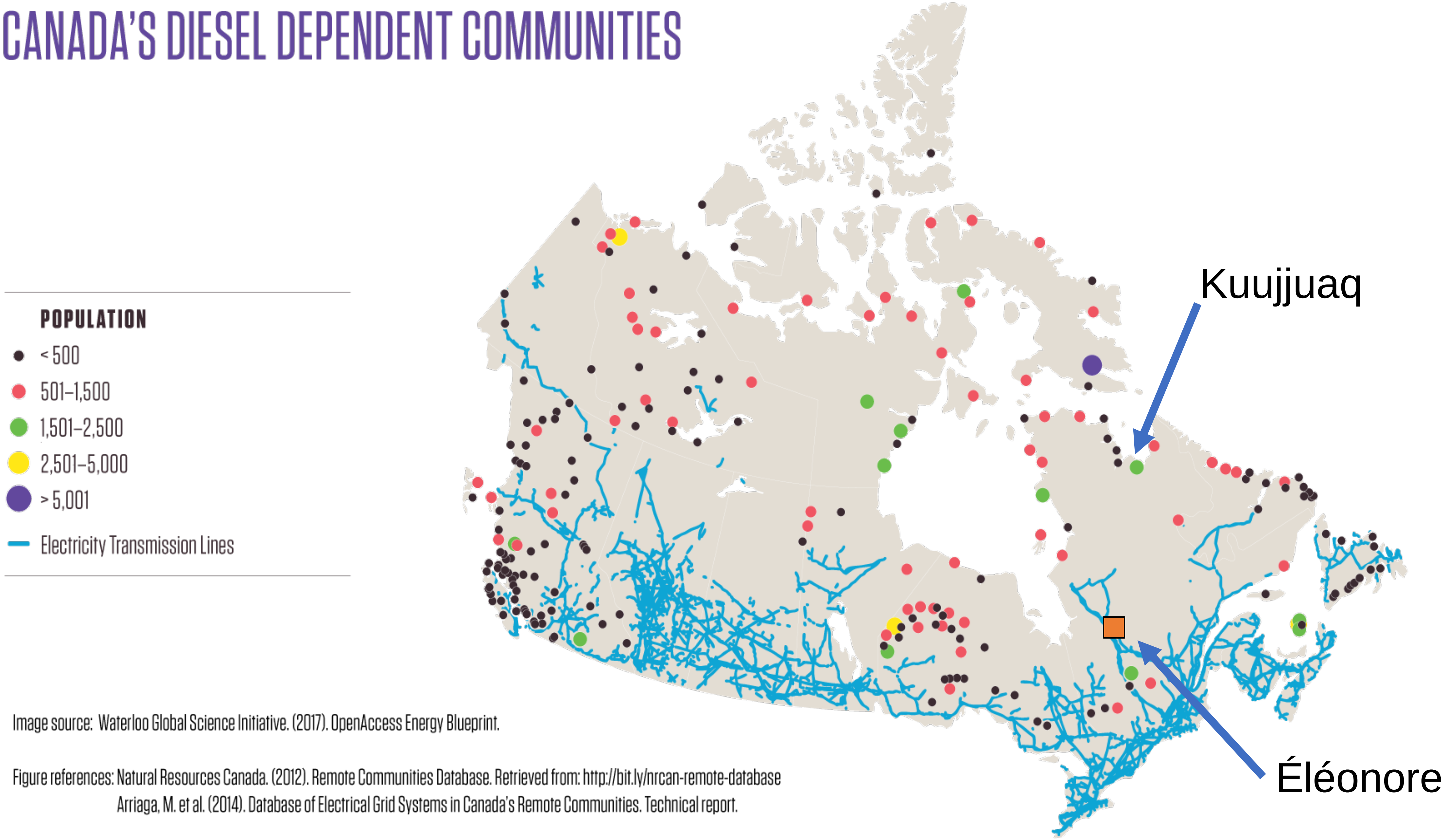
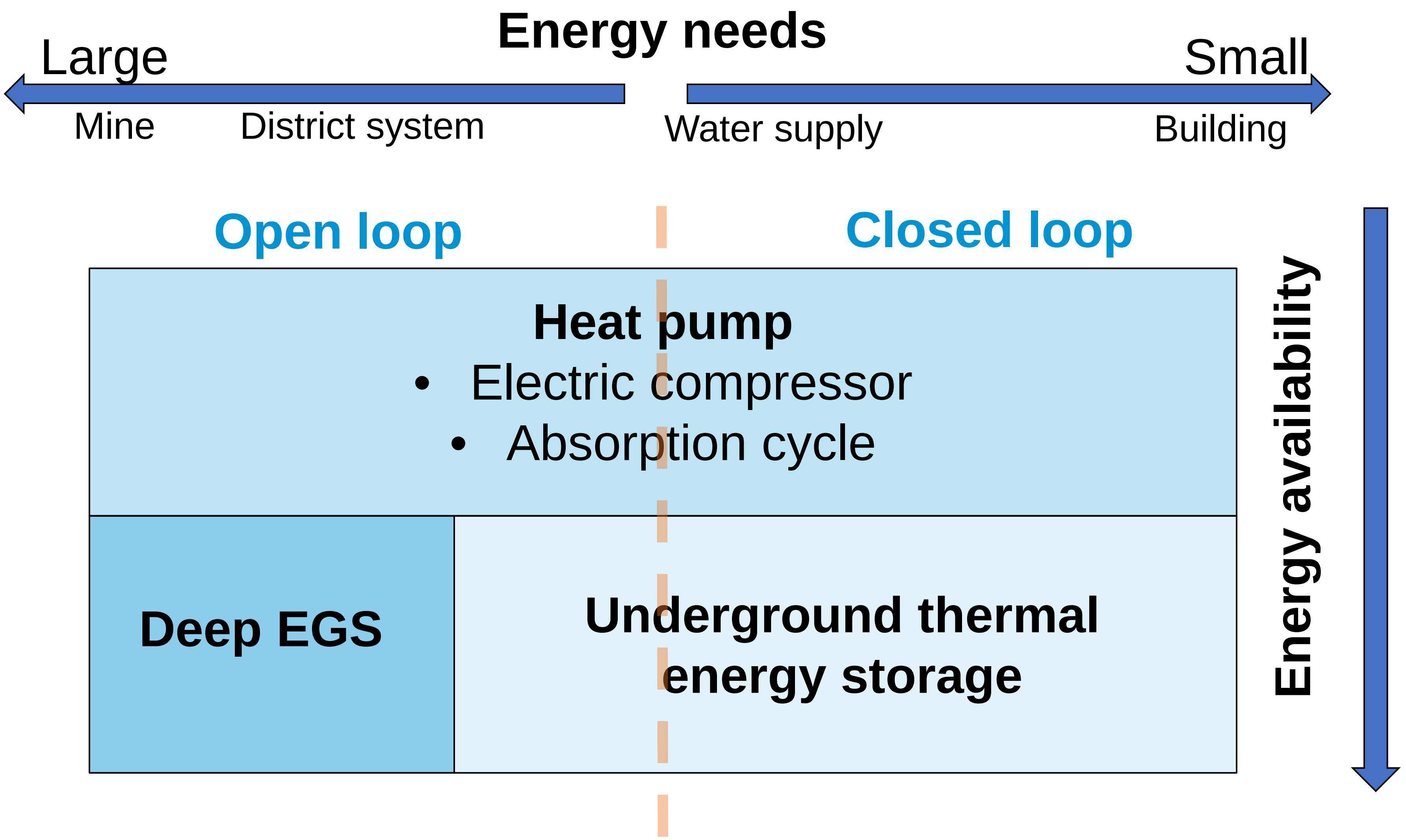


Image source: Waterloo Global Science Initiative. (2017). OpenAccess Energy Blueprint.

Figure references: Natural Resources Canada. (2012). Remote Communities Database. Retrieved from: http://bit.ly/nrcan-remote-database
Arriaga, M. et al. (2014). Database of Electrical Grid Systems in Canada's Remote Communities. Technical report.

Low temperature geothermal heating options



ᓇᑯᕐᒦᒃ - Nakurmiik

Jasmin Raymond, Chrystel Dezayes, Edgardo Alvarado, Evelyn Gunawan
Felix-Antoine Comeau, Ines Kanzari, Mafalda M. Miranda, Nicolò Giordano

jasmin.raymond@inrs.ca

HÁSKÓLINN Í REYKJAVÍK REYKJAVIK UNIVERSITY

brgm Géosciences pour une Terre durable

Centre d'études nordiques

Institut nordique du Québec Together for the North

INRS UNIVERSITÉ DE RECHERCHE