Monitoring and modelling groundwater flow dynamics in a glacial aquifer system with degrading & discontinuous permafrost (Umiujaq, Nunavik, Canada)

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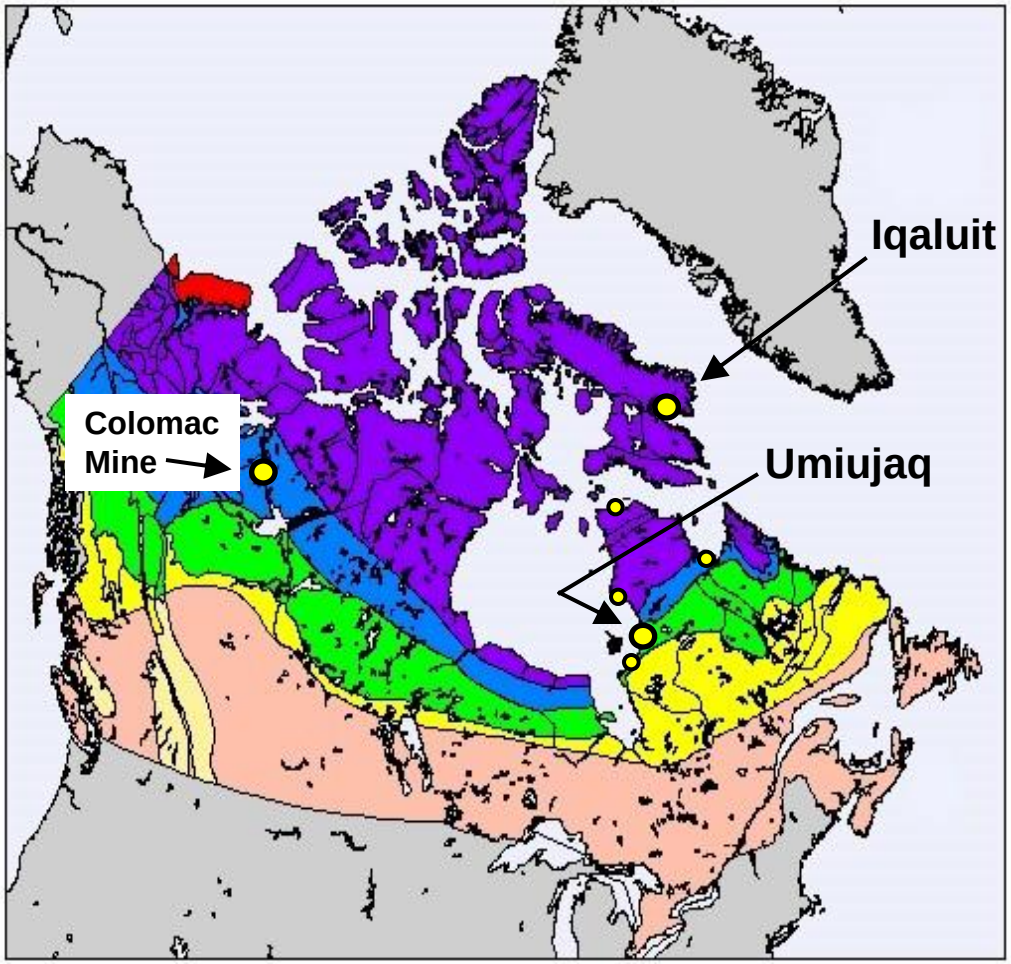
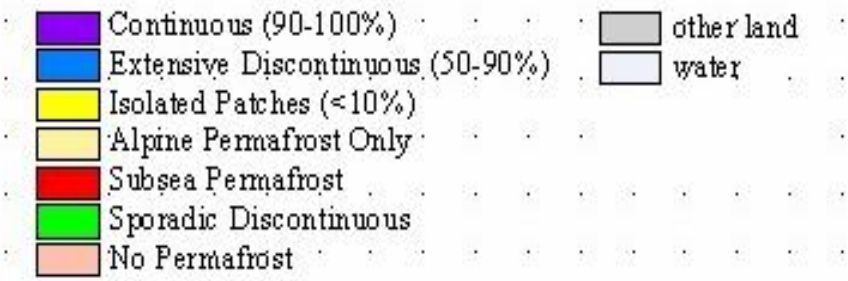
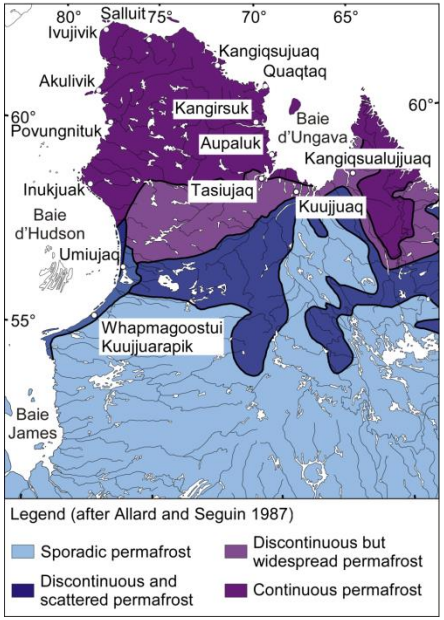
NATURWISSENSCHAFTLICHE FAKULTÄT

Research sites in Canadian permafrost

Permafrost map of Canada

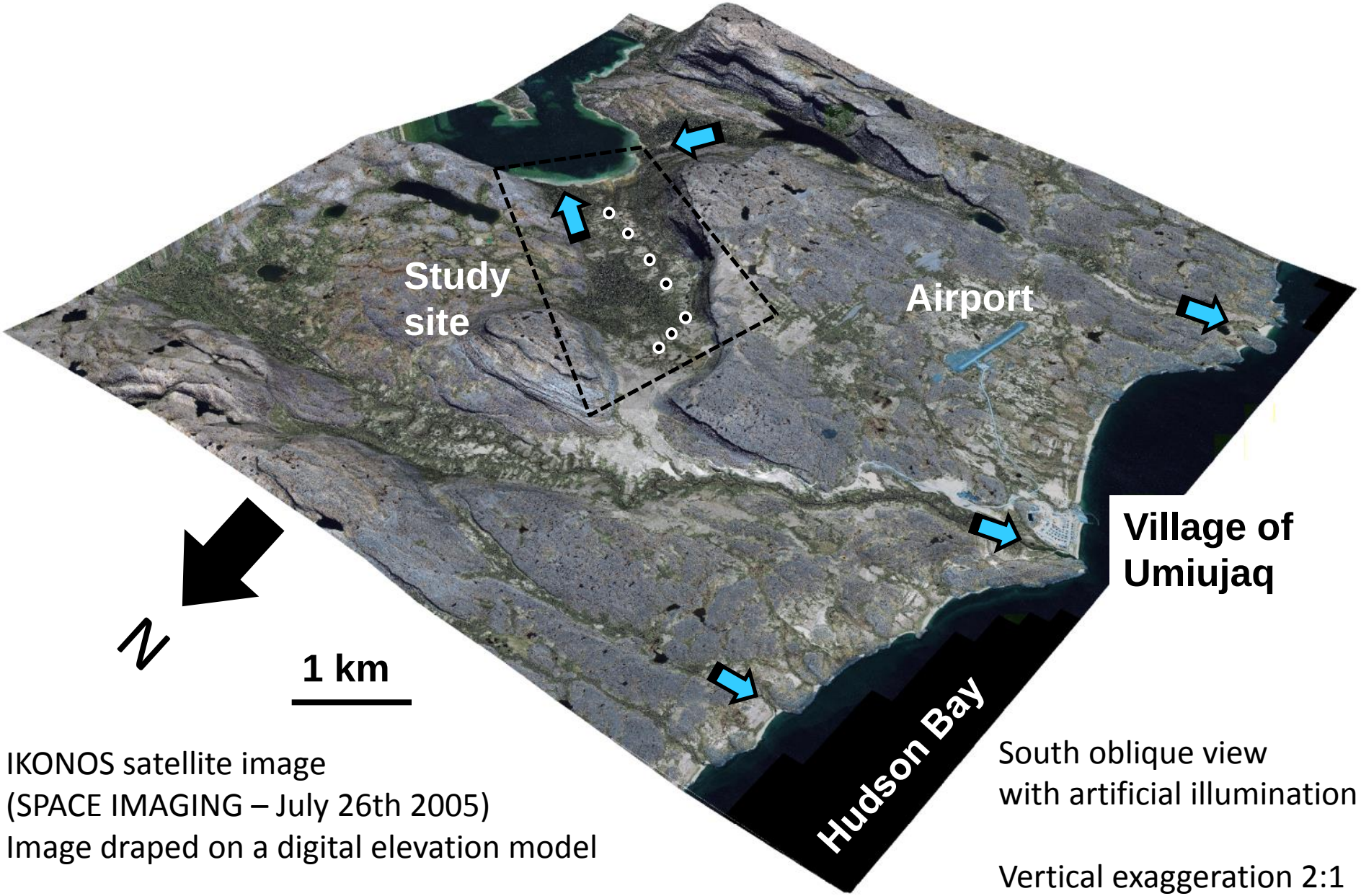






Heginbottom et al. 1995

Immatsiak network location

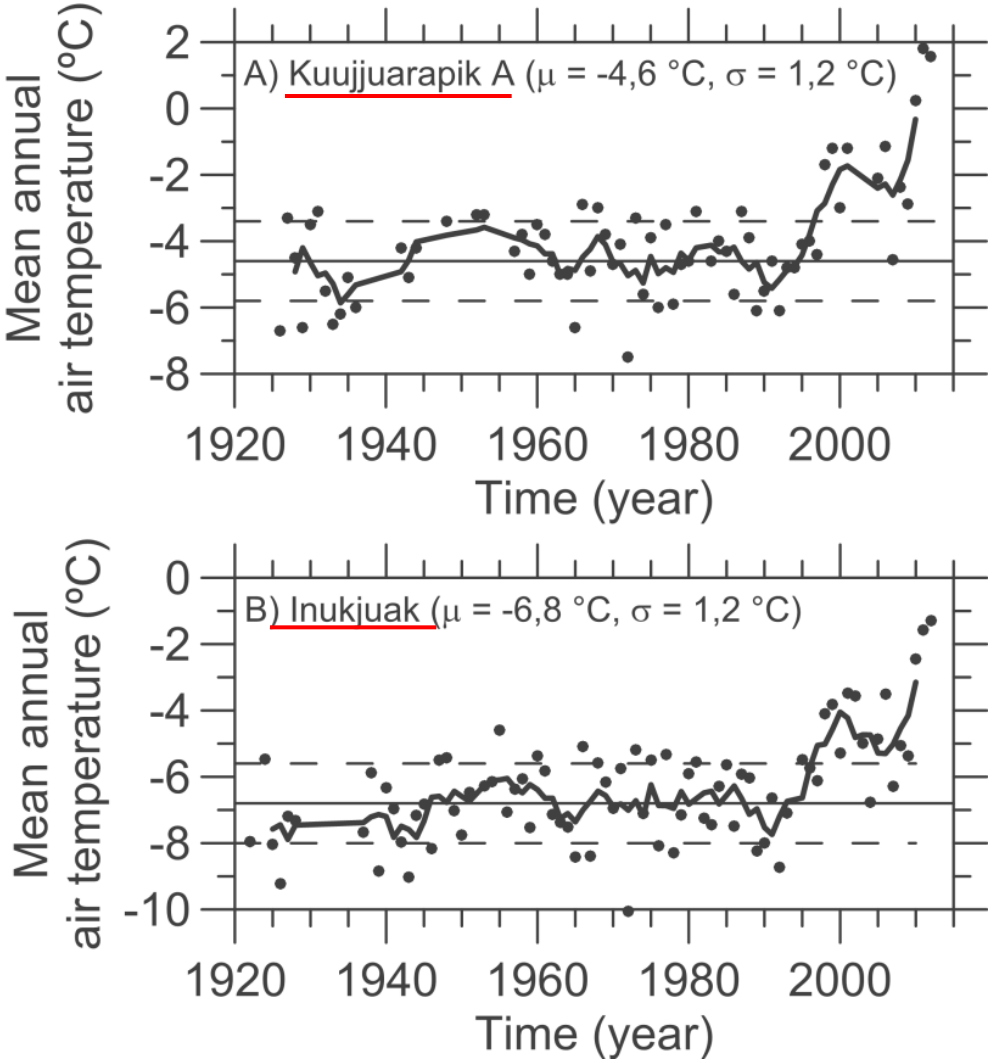


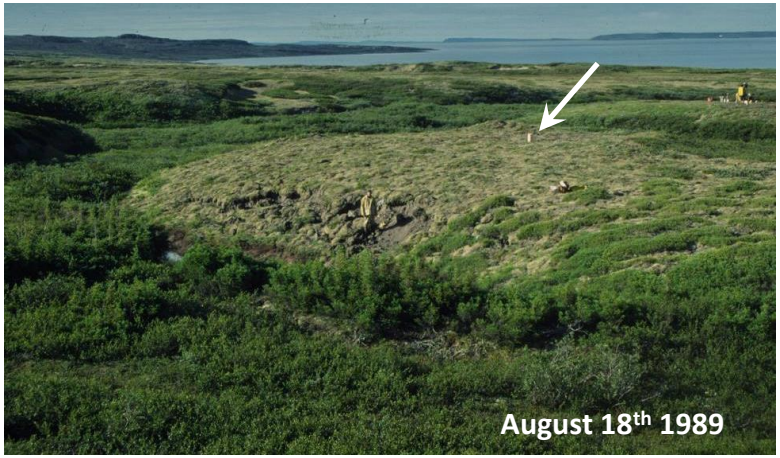
IKONOS satellite image
(SPACE IMAGING – July 26th 2005)
Image draped on a digital elevation model

South oblique view
with artificial illumination

Vertical exaggeration 2:1

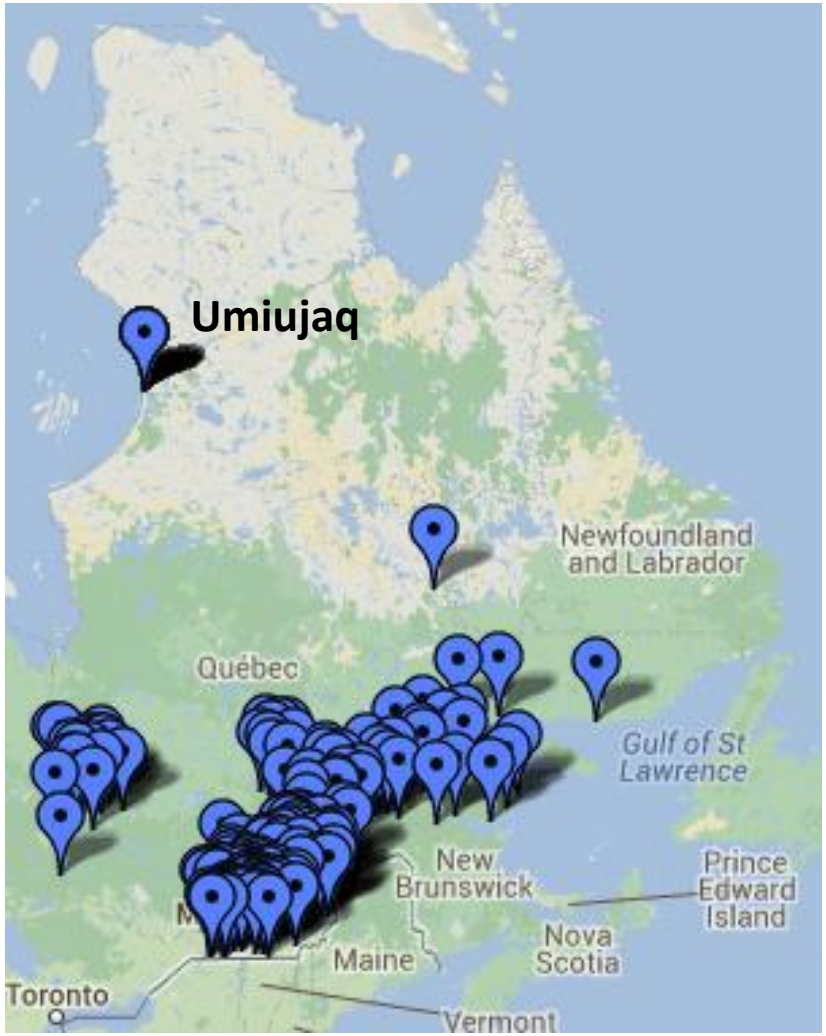
Recent climate variability and impacts





Motivation and Objectives

- Provincial Groundwater Monitoring Network
- Assess the impacts of climate change on groundwater resources (Quebec Climate Change Plan)
- Immatsiak network (meaning "source of fresh water" in Inuktitut), Umiujaq
- Study the groundwater dynamics in permafrost environments
- Hypothesis 1: Improved groundwater availability
- Hypothesis 2: Groundwater flow increases permafrost degradation



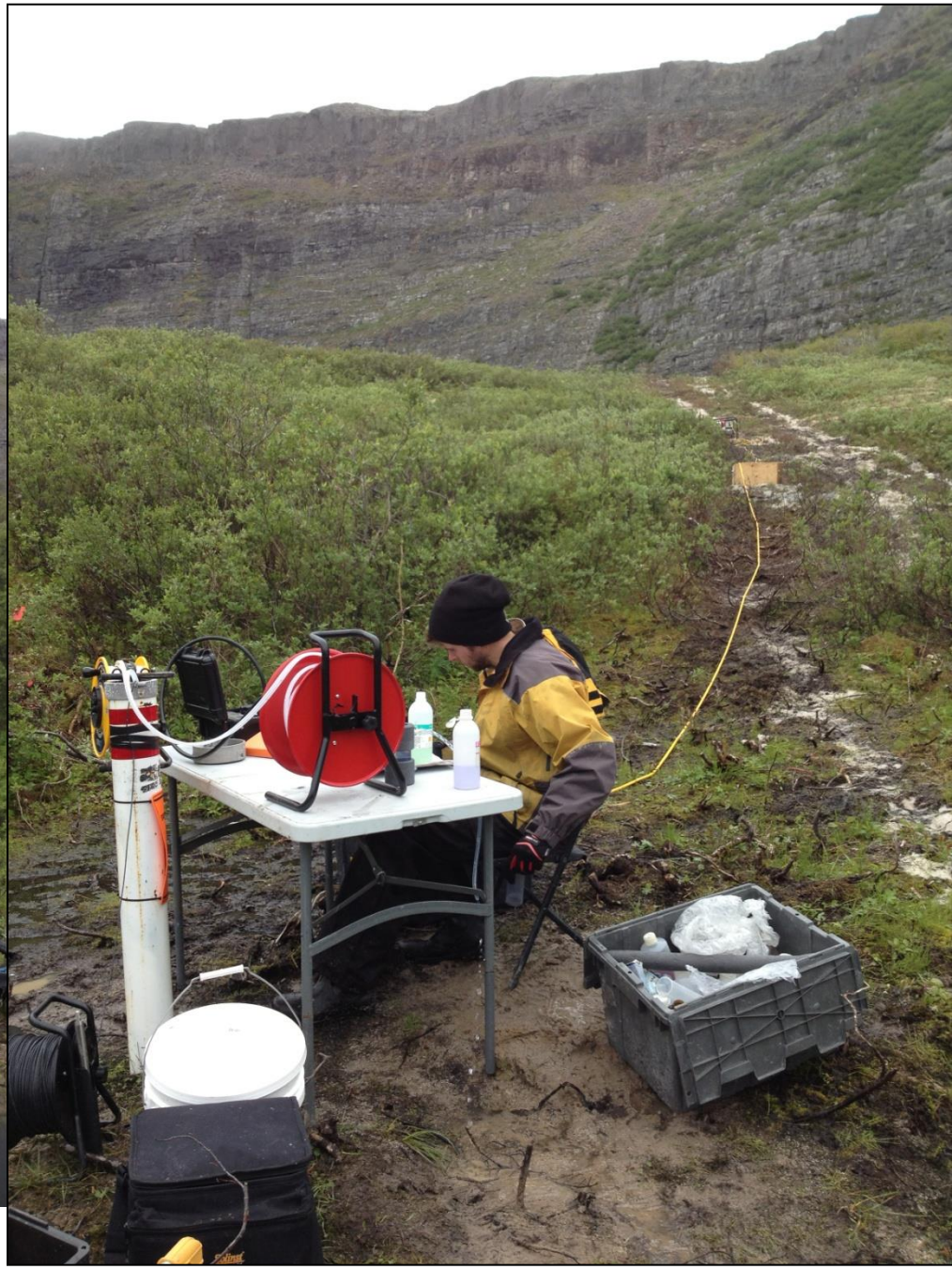
http://www.mddep.gouv.qc.ca/eau/piezo/index.htm


Airport road


Kilutaq Road
Hudson Road
ᐊᓗᒃᑲᓂᑦ
ARRÊT
STOP

Drilling campaign June 2012

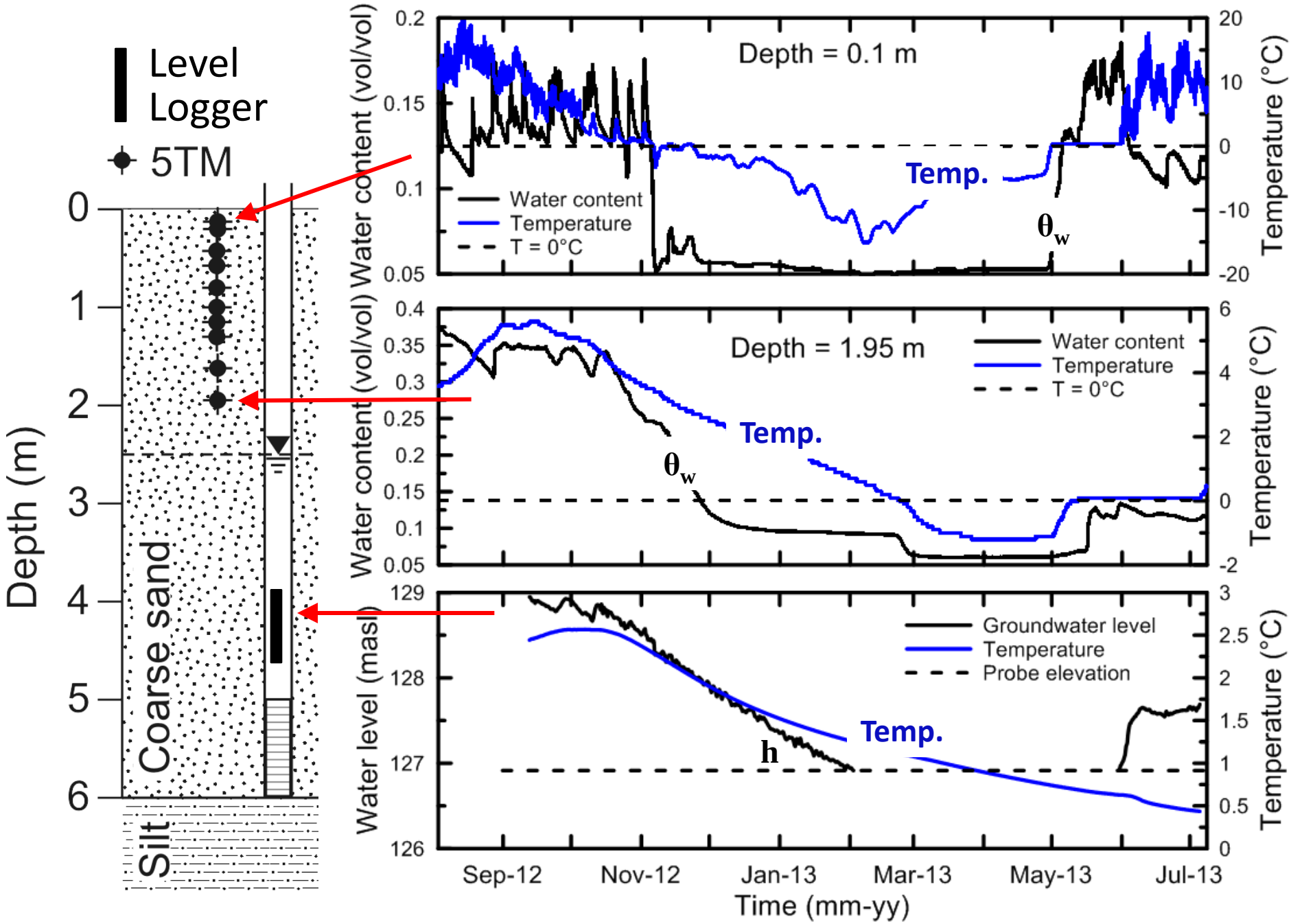
Sampling campaign July 2013



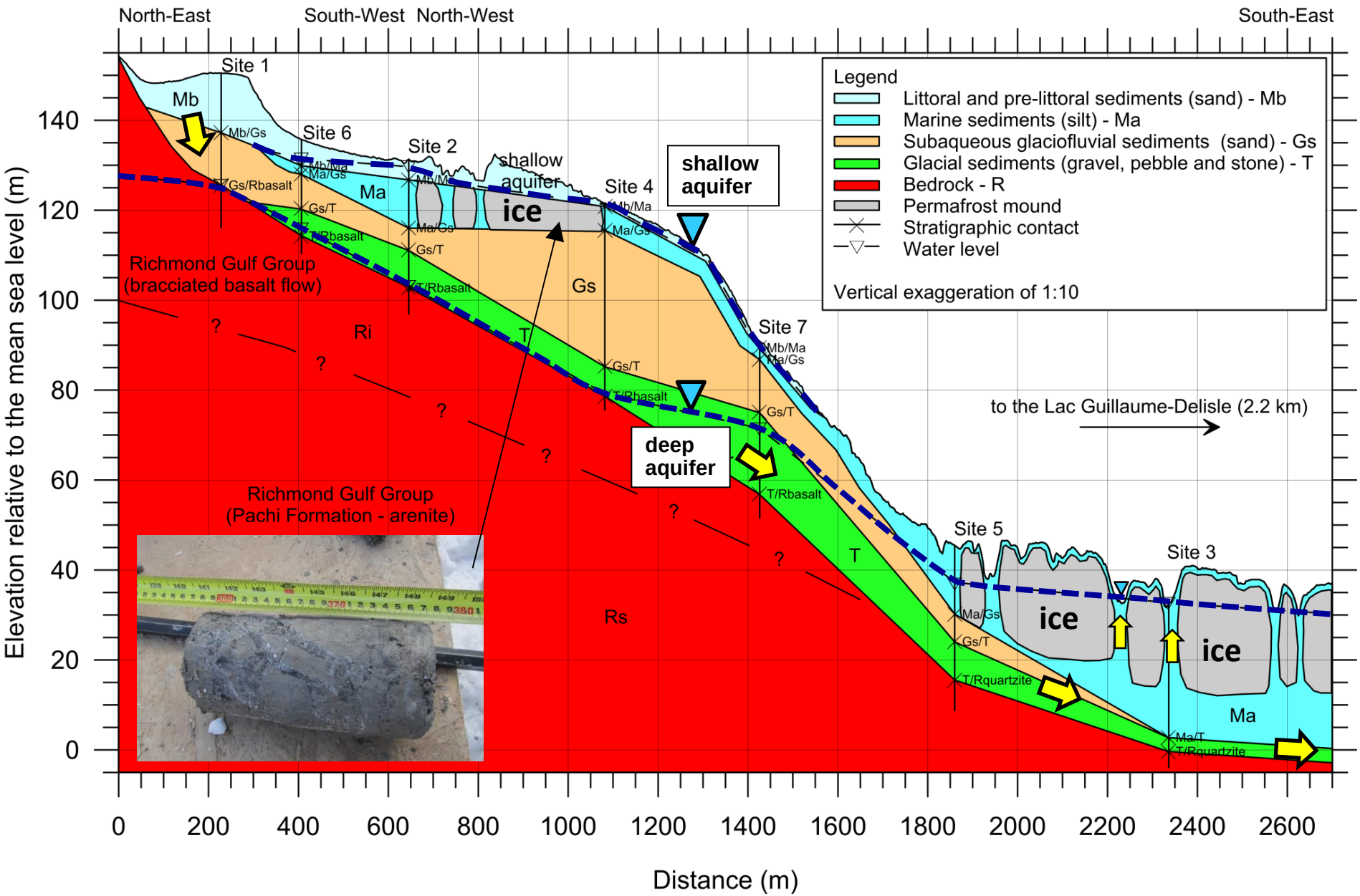
July 2013


November 2014


November 2014


Level Logger
5TM
Depth (m)
Coarse sand
Silt
Depth = 0.1 m
Water content
Temperature
T = 0°C
Temp.
θw
Water content (vol/vol)
Temperature (°C)
Depth = 1.95 m
Water content
Temperature
T = 0°C
Temp.
θw
Water content (vol/vol)
Temperature (°C)
Groundwater level
Temperature
Probe elevation
Temp.
h
Water level (masl)
Temperature (°C)
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Time (mm-yy)

Conceptual Cross-Section

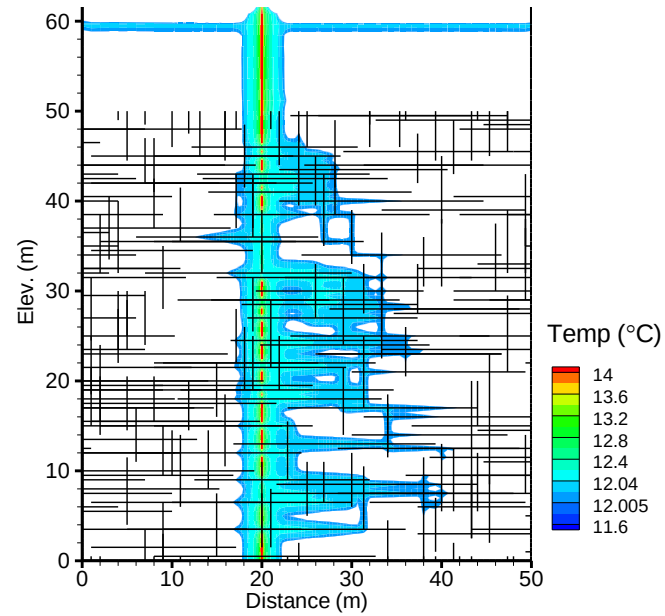


HEATFLOW/SMOKER Model

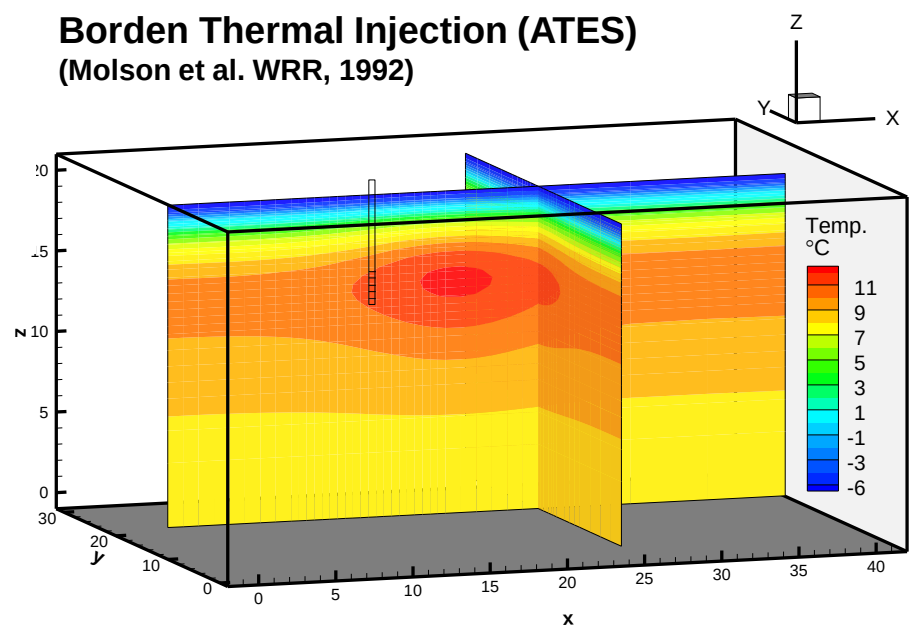
(Molson & Frind 2014)

- **3D Galerkin finite element**
- **Deformable brick elements**
- **PCG symmetric matrix solver**
- **Porous medium & discrete fractures**
- **Heat, mean age & mass transport**
- **Equilibrium geochemistry**
- **Liquid & ice phases, latent heat**
- **Picard iteration**

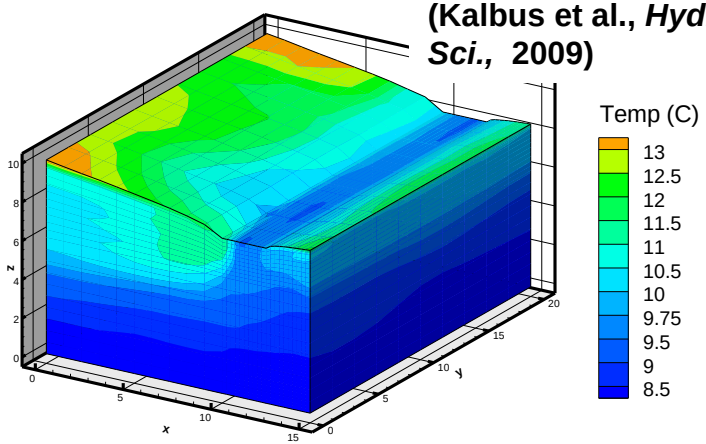
Thermal tracers: DFN
(Pehme et al., J. Hydrol. 2013)



Borden Thermal Injection (ATES)
(Molson et al. WRR, 1992)



GW/SW Interaction
(Kalbus et al., *Hydrol. Earth Syst. Sci.*, 2009)



Numerical Simulation Approach:

HEATFLOW/SMOKER

Surface b.c.:

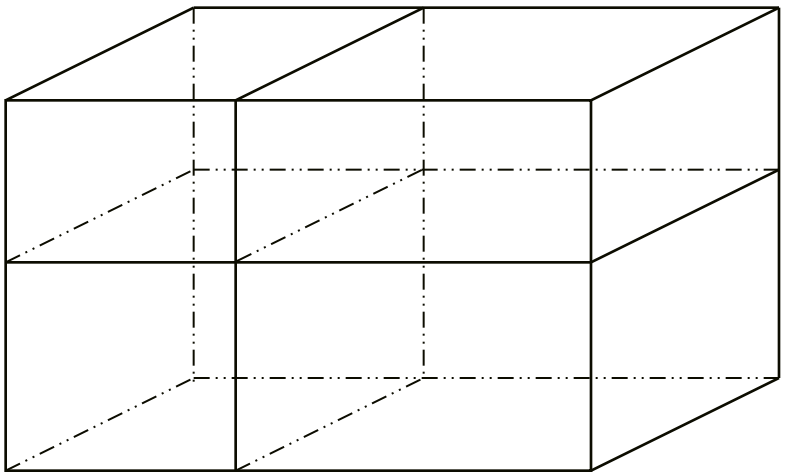
$$J_i = \left(\frac{\lambda_u}{B_z}\right)(T_a - T_s) + (q \cdot c_w \rho_w) \cdot (T_q - T_s)$$

Porous Matrix :

$$\frac{\partial}{\partial x_i}\left[K_{i,j}(T)\left(\frac{\partial \psi}{\partial x_j} + \rho_r(T) \cdot \bar{n}_j\right)\right] - \sum_{k=1}^{N} Q_k(t) \cdot \delta(x_k, y_k, z_k) = S_s \frac{\partial \psi}{\partial t}$$

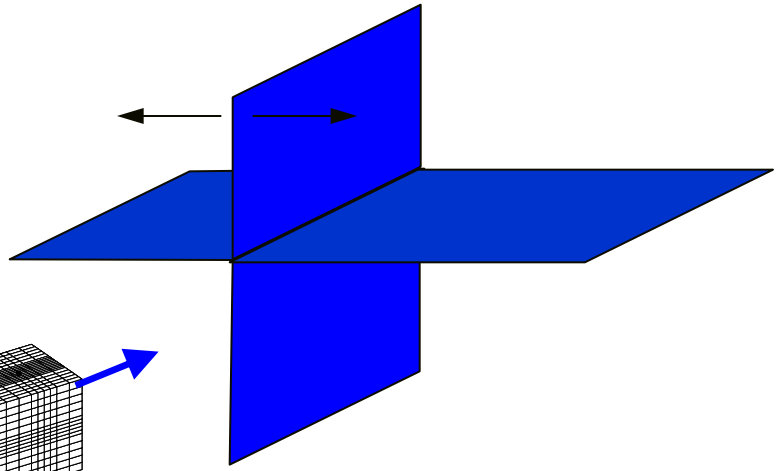
$$-\frac{\partial}{\partial x_i}\left(\theta S_w c_w \rho_w v_i T\right) + \frac{\partial}{\partial x_i}\left(\bar{\lambda} + \theta S_w c_w \rho_w D\right)\frac{\partial T}{\partial x_j} + \Omega = \frac{\partial\left(C_o T\right)}{\partial t}$$

$$C_o = \theta S_w c_w \rho_w + \theta S_i c_i \rho_i + (1-\theta) c_s \rho_s + \theta \rho_i L\left(\frac{\partial S_w}{\partial T}\right)$$

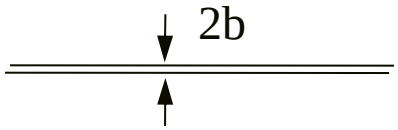


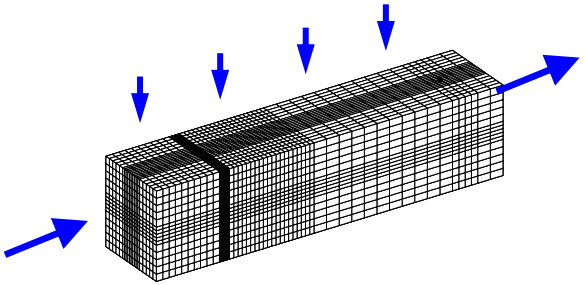
Fractures:

$$-\frac{\partial(S_w c_w \rho_w \bar{v}_i T')}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\bar{\lambda} + S_w c_w \rho_w D \frac{\partial T'}{\partial x_j}\right) + \frac{S_w c_w \rho_w D}{b}\left[\frac{\partial T}{\partial z}\right]_{z=\pm b} = \frac{\partial C_o T'}{\partial t}$$

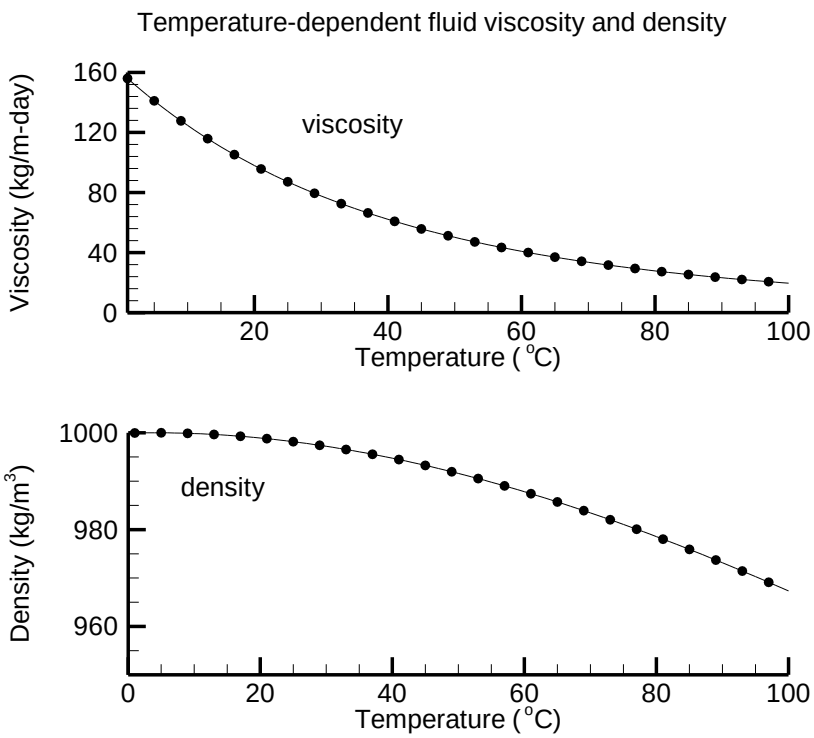


Fracture velocities: $v = \frac{-(2b)^2}{12\mu}\rho g \nabla h$

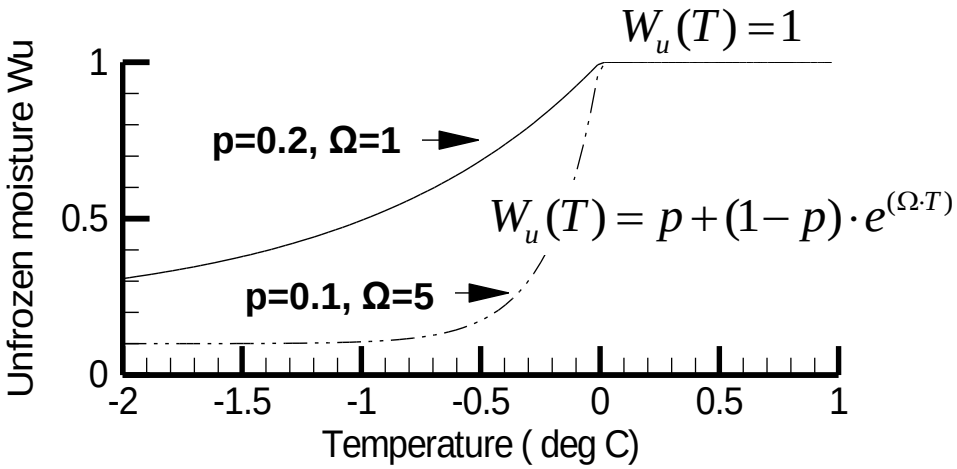




Fluid Viscosity and Density Functions:



Frozen/Unfrozen Water:



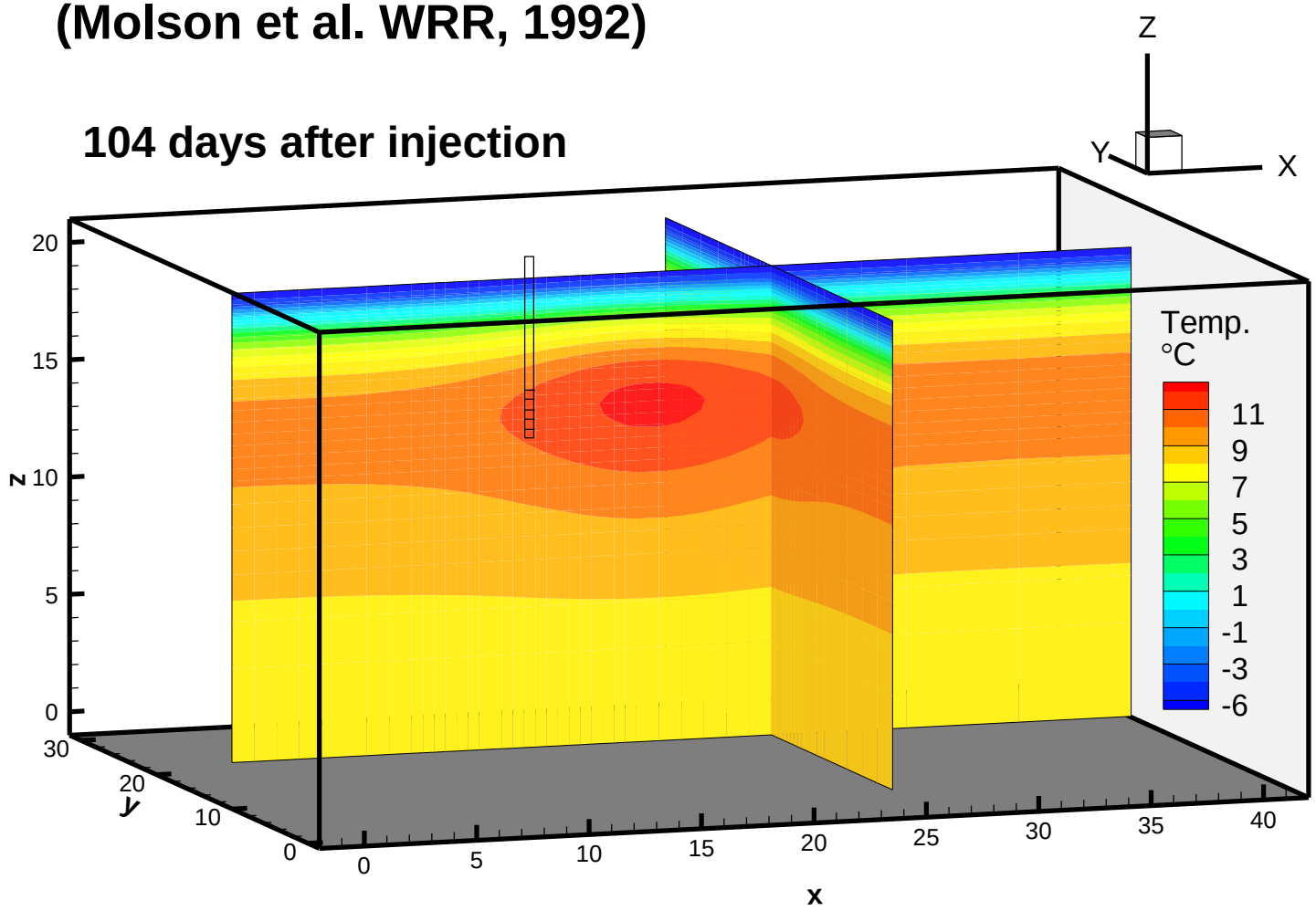
Relative Permeability k_r:

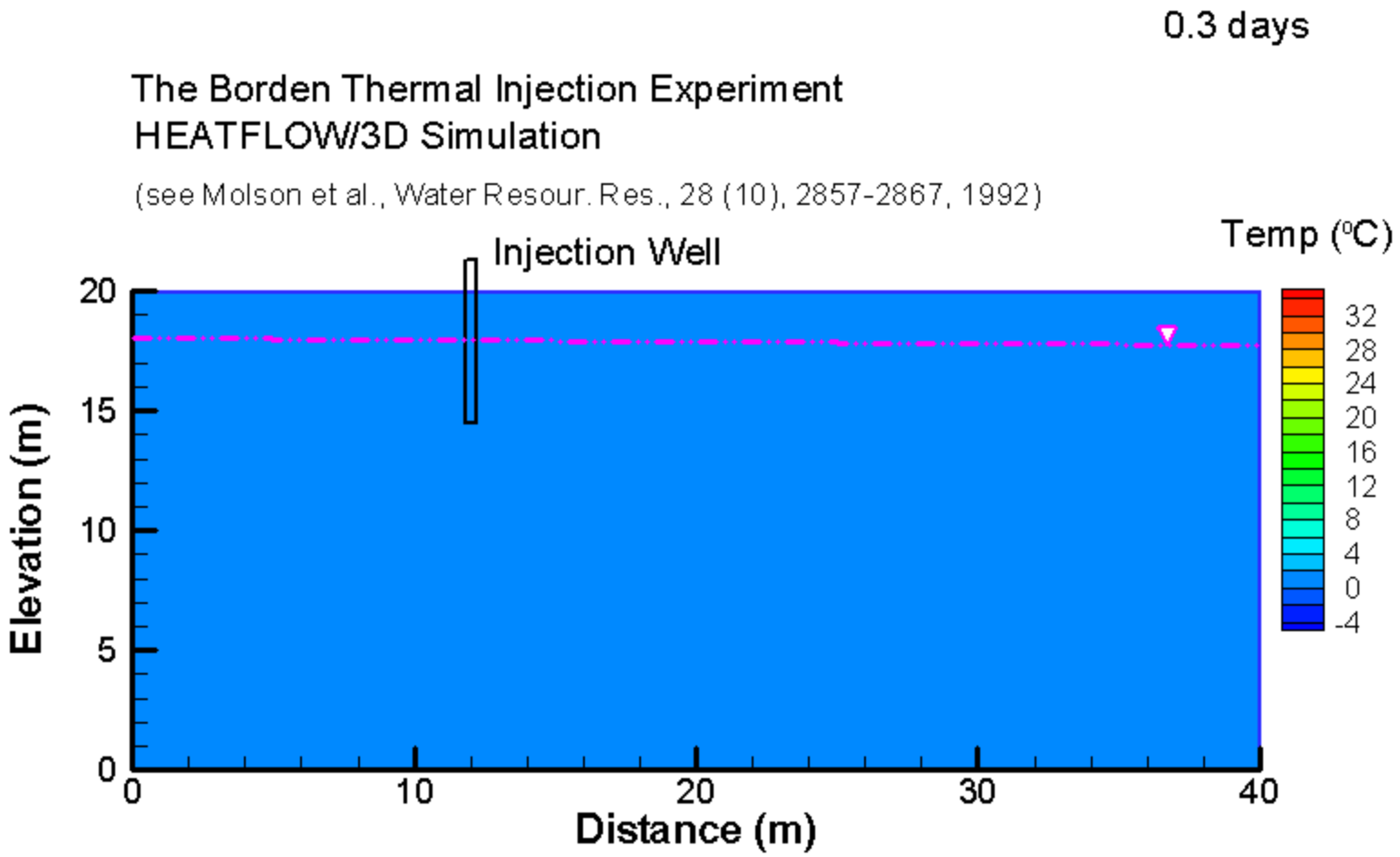
$$k_r = \max\left[\left(\frac{Wu(T)-p}{1-p}\right)^4,\ 10^{-6}\right]$$

Borden Thermal Injection

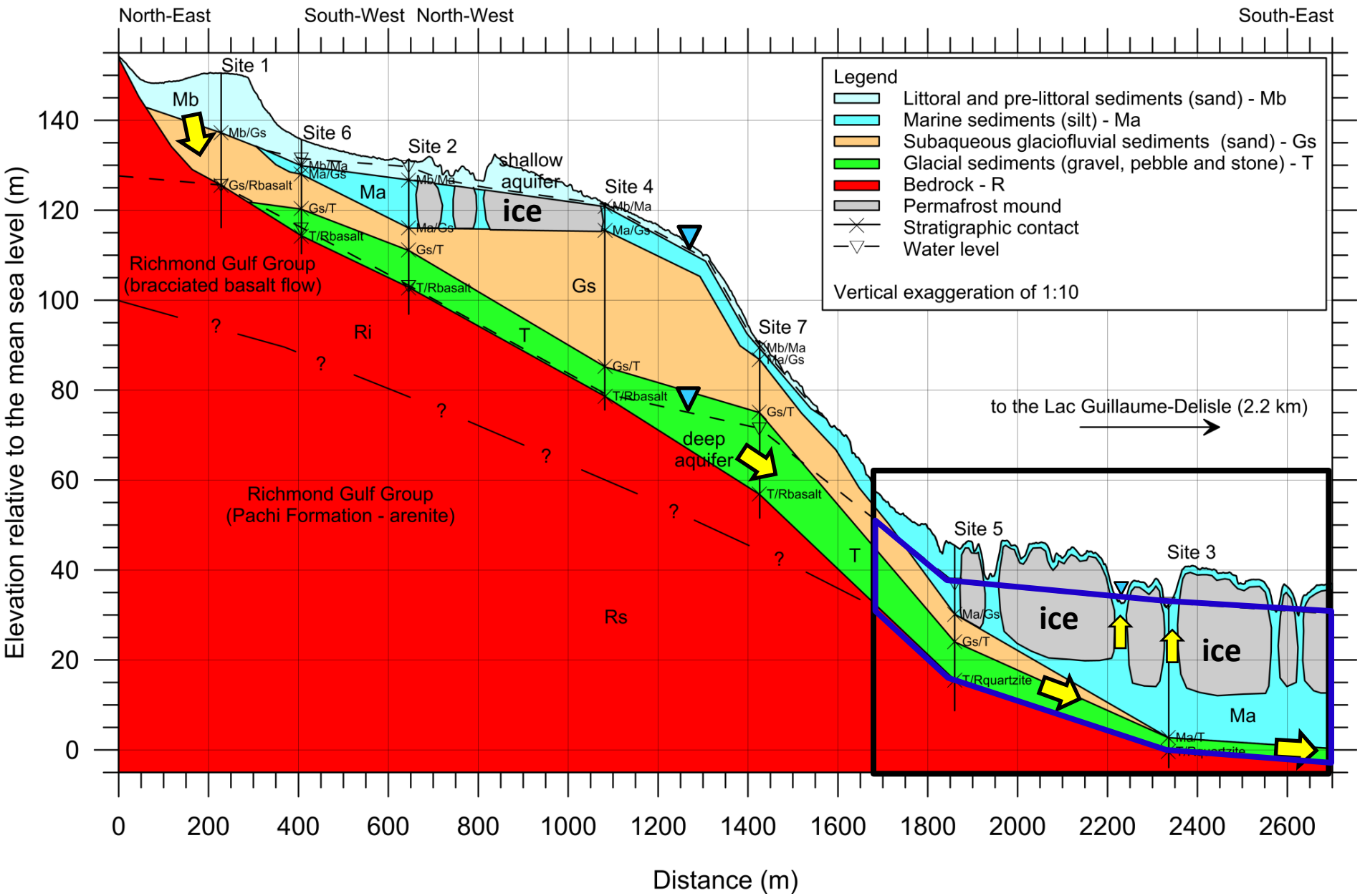
(Molson et al. WRR, 1992)

104 days after injection

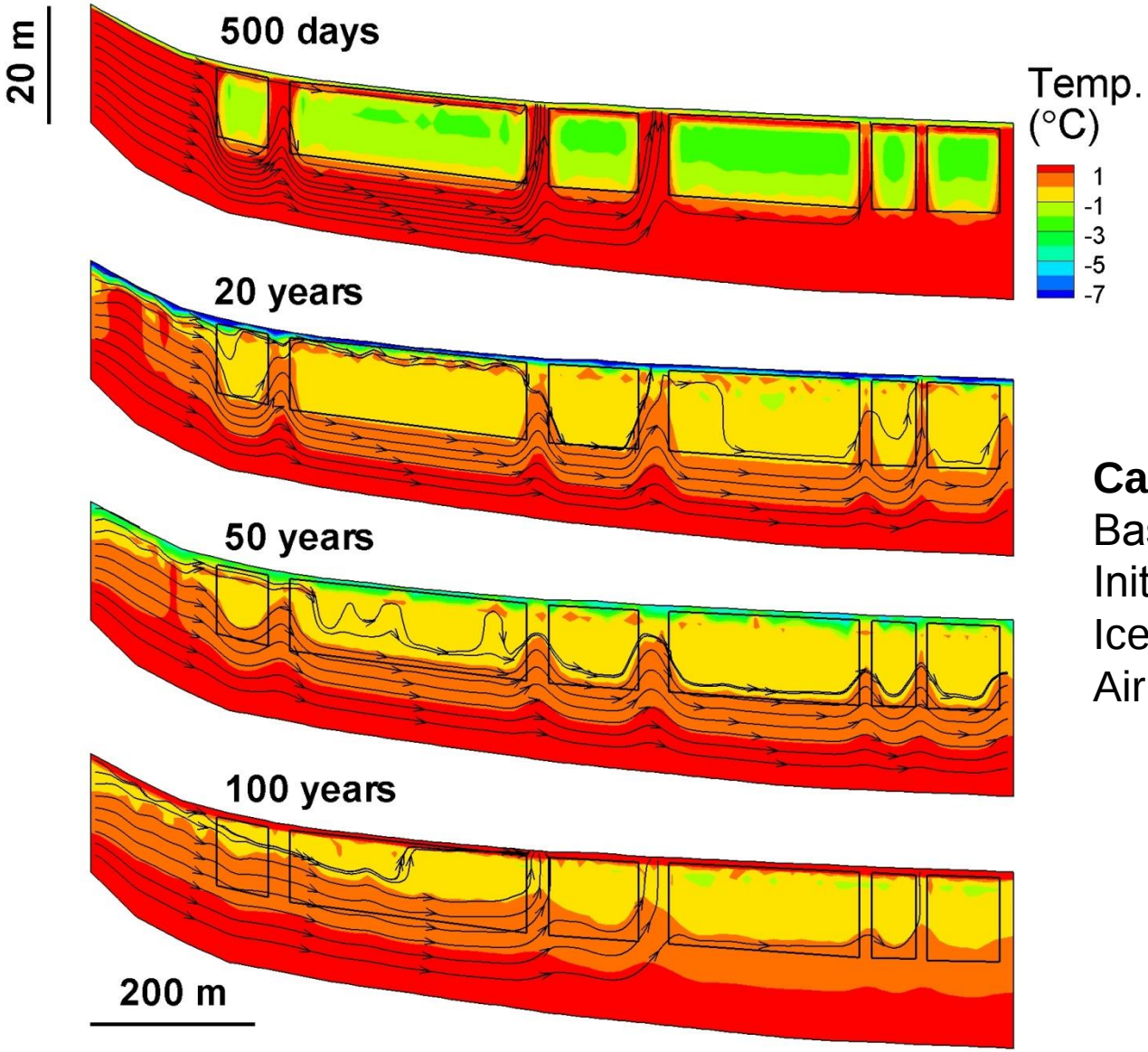



0.3 days
The Borden Thermal Injection Experiment
HEATFLOW/3D Simulation
(see Molson et al., Water Resour. Res., 28 (10), 2857-2867, 1992)
Injection Well
Temp (°C)
32
28
24
20
16
12
8
4
0
-4
Elevation (m)
20
15
10
5
0
0
10
20
30
40
Distance (m)

Conceptual Cross-Section



Permafrost Evolution: Umiujaq
Temperature & flow lines



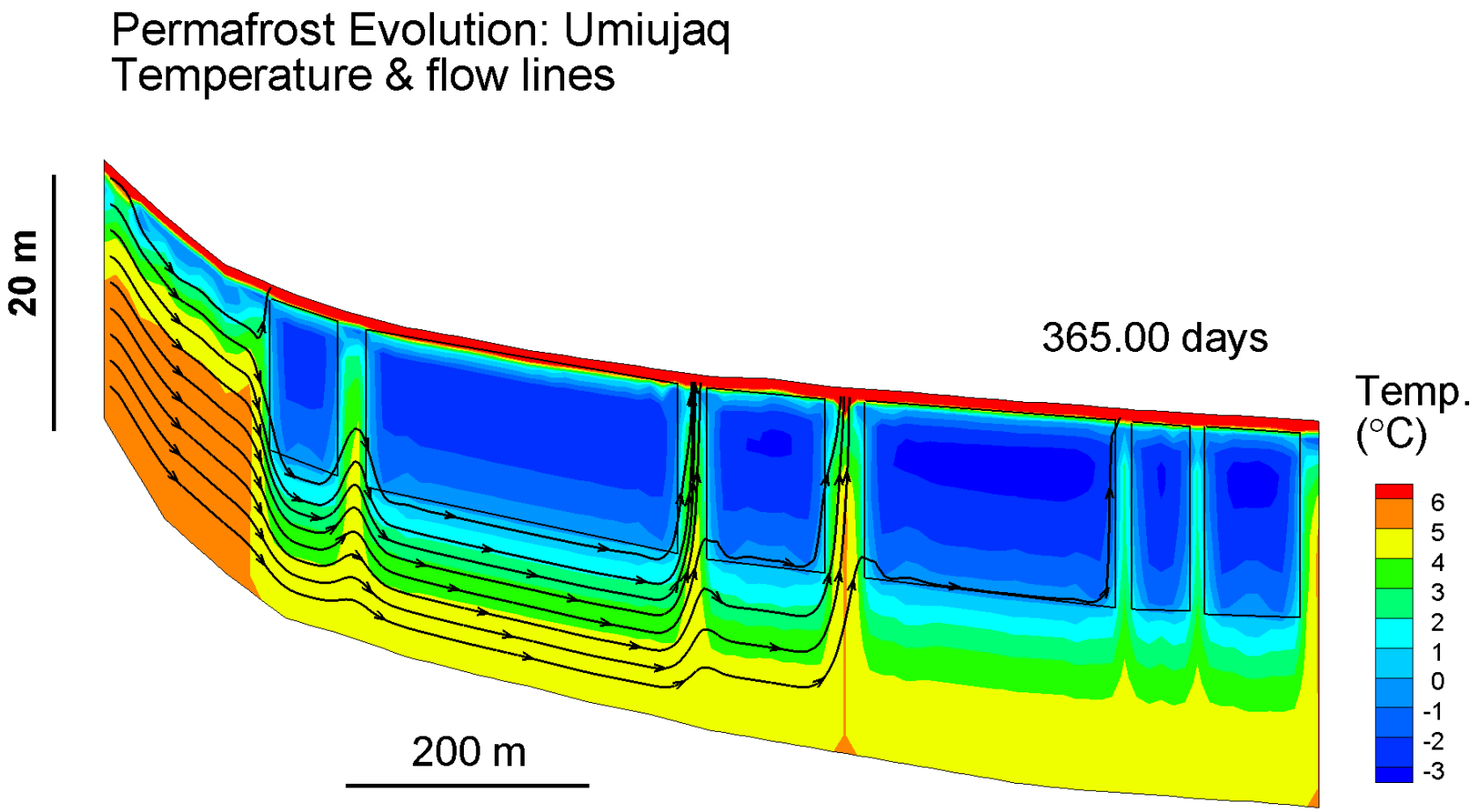
Case B: (warmer)

Base T= +2 ˚C

Initial T= +5 ˚C

Ice T= -5 ˚C

Air T_{min}= -20, A= +25 ˚C


Permafrost Evolution: Umiujaq
Temperature & flow lines
20 m
365.00 days
Temp.
(°C)
6
5
4
3
2
1
0
-1
-2
-3
200 m

Acknowledgements

Développement durable, Environnement et Lutte contre les changements climatiques

Québec

Stratégie de déploiement du réseau Immatsiak 2010-2013 …….. $ 400,000

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Strategic Project Grant 2013-2016 ..... $ 530,166

Fonds de recherche Nature et technologies

Québec

Canada Foundation for Innovation

Fondation canadienne pour l'innovation

Centre d'études nordiques

UNIVERSITÉ LAVAL

Program of Energy Research and Development (PERD)

Indian & Northern Affairs Canada (INAC)