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

R. Therrien[1,2], J. Molson[1,2], J.M. Lemieux[1,2], R. Fortier[1,2], M. Ouellet[3]
J. Barth[4], R. Murray[1,2], D. Banville[1,2], J. Sottas[1,2], M. Cochand[1,2]

(1) Université Laval

(2) Centre d'études nordiques
CEN Centre for Northern Studies

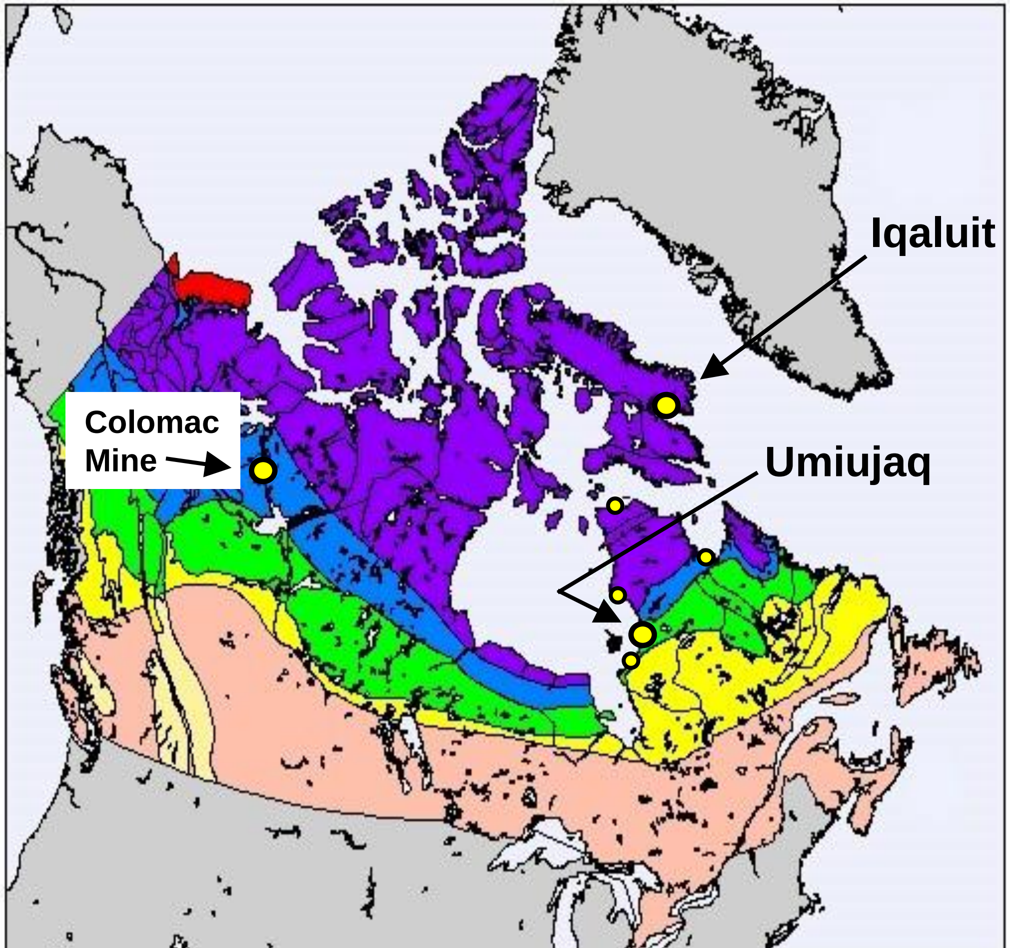
(3) Développement durable, Environnement et Lutte contre les changements climatiques
Québec

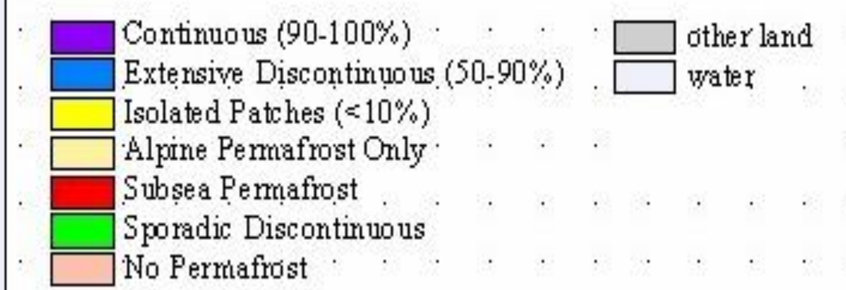
(4) FAU Friedrich-Alexander Universität Erlangen-Nürnberg
Naturwissenschaftliche Fakultät

Research sites in Canadian permafrost

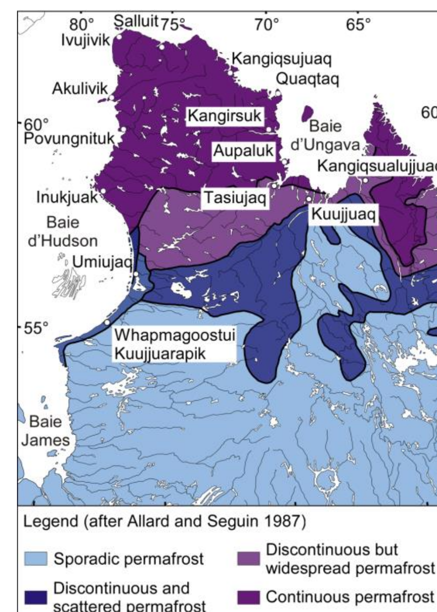
UNIVERSITÉ LAVAL

Permafrost map of Canada

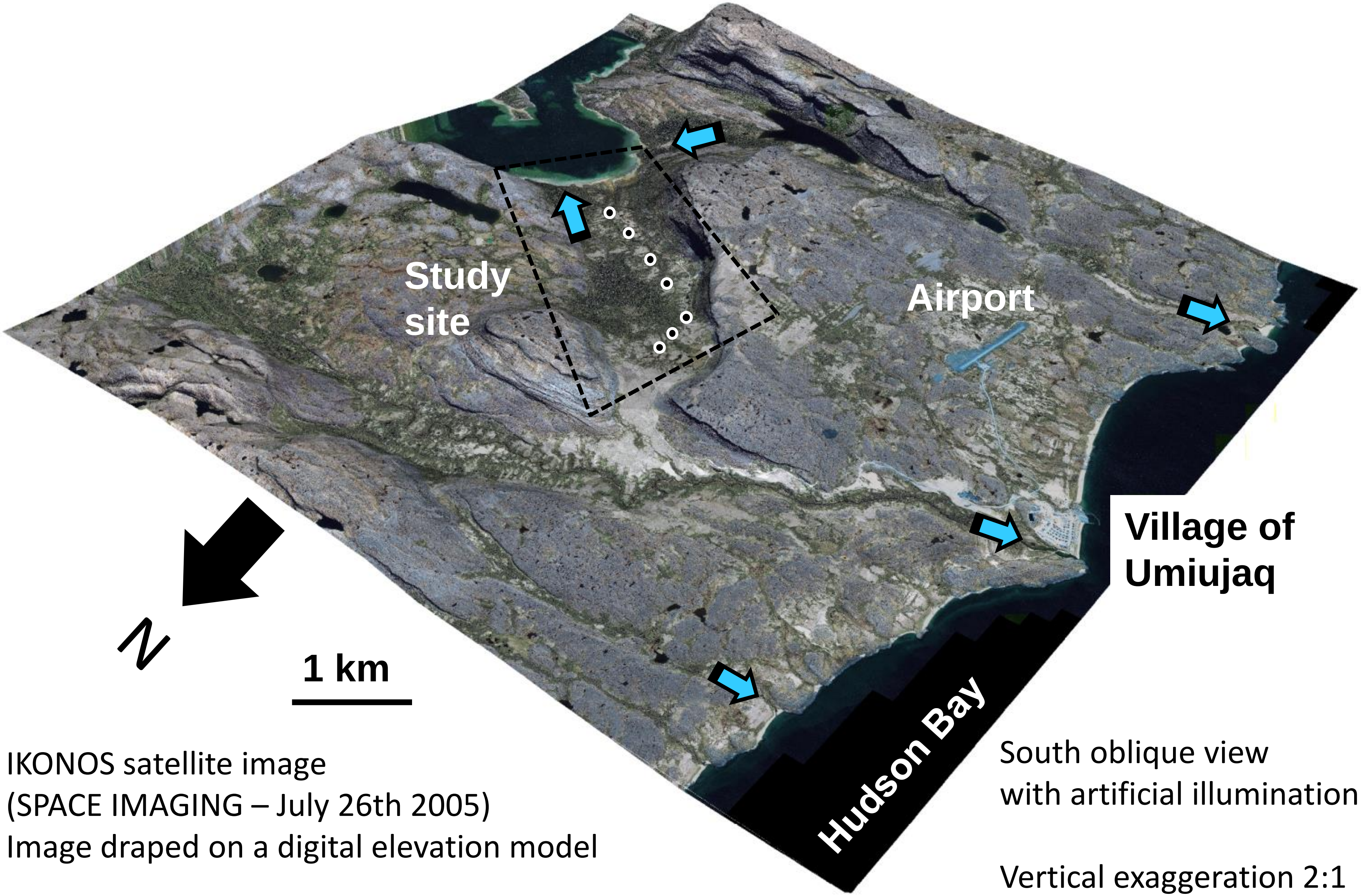




Heginbottom et al. 1995



Immatsiak network location

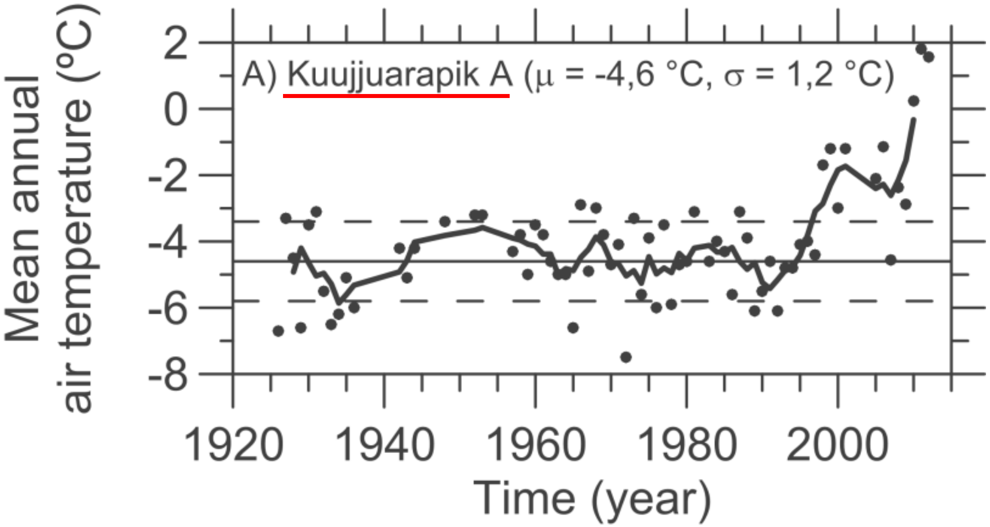


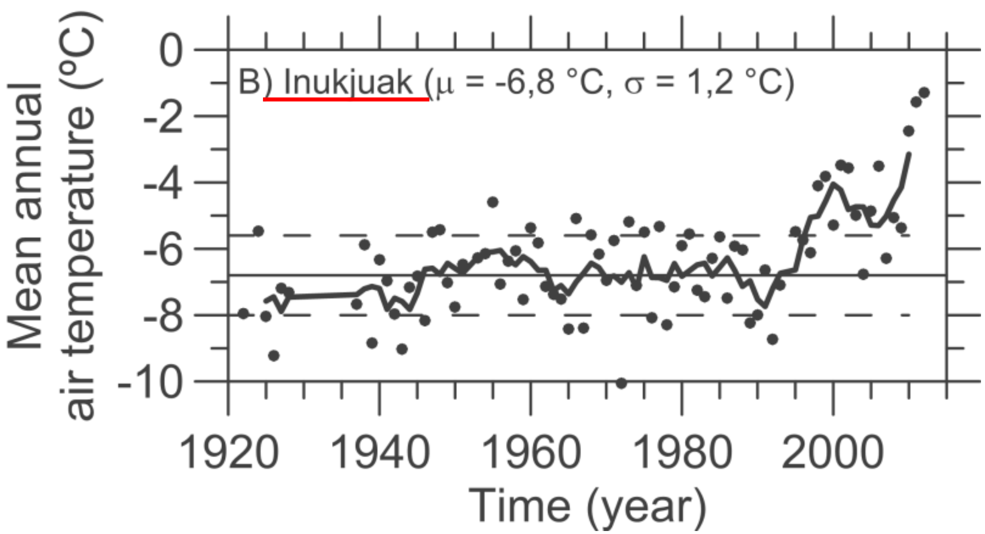
IKONOS satellite image
(SPACE IMAGING – July 26th 2005)
Image draped on a digital elevation model

South oblique view
with artificial illumination

Vertical exaggeration 2:1

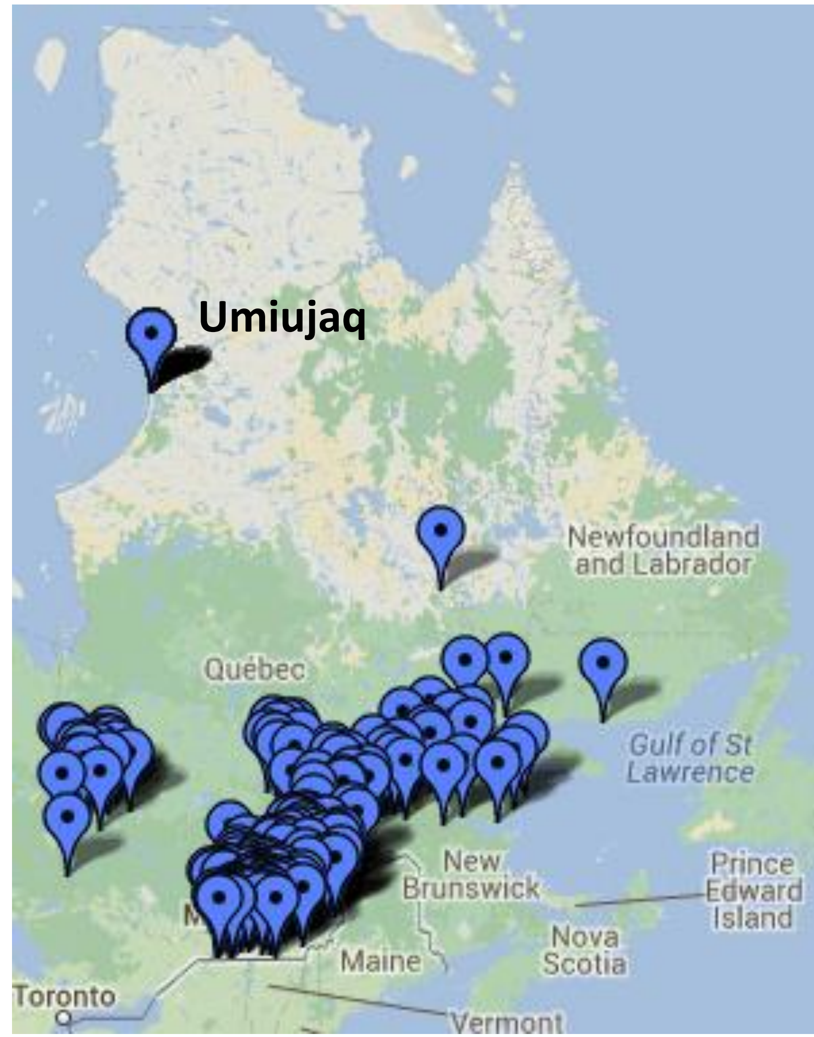
Recent climate variability and impacts



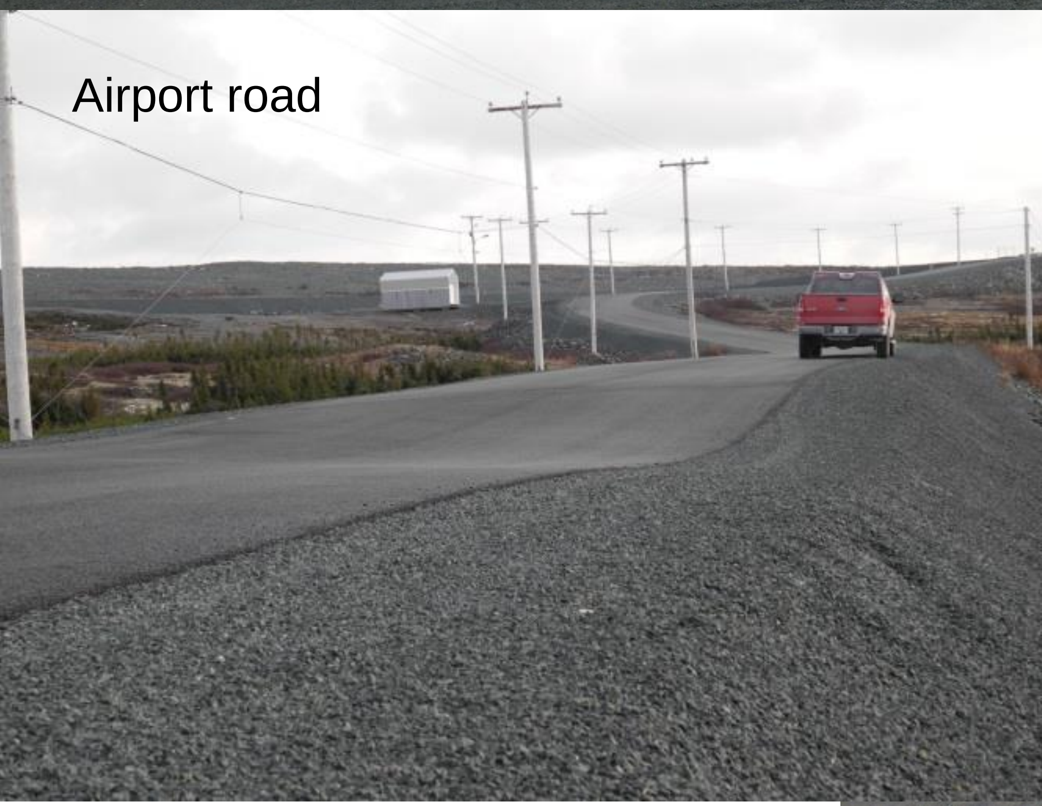


Motivation and Objectives

- 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



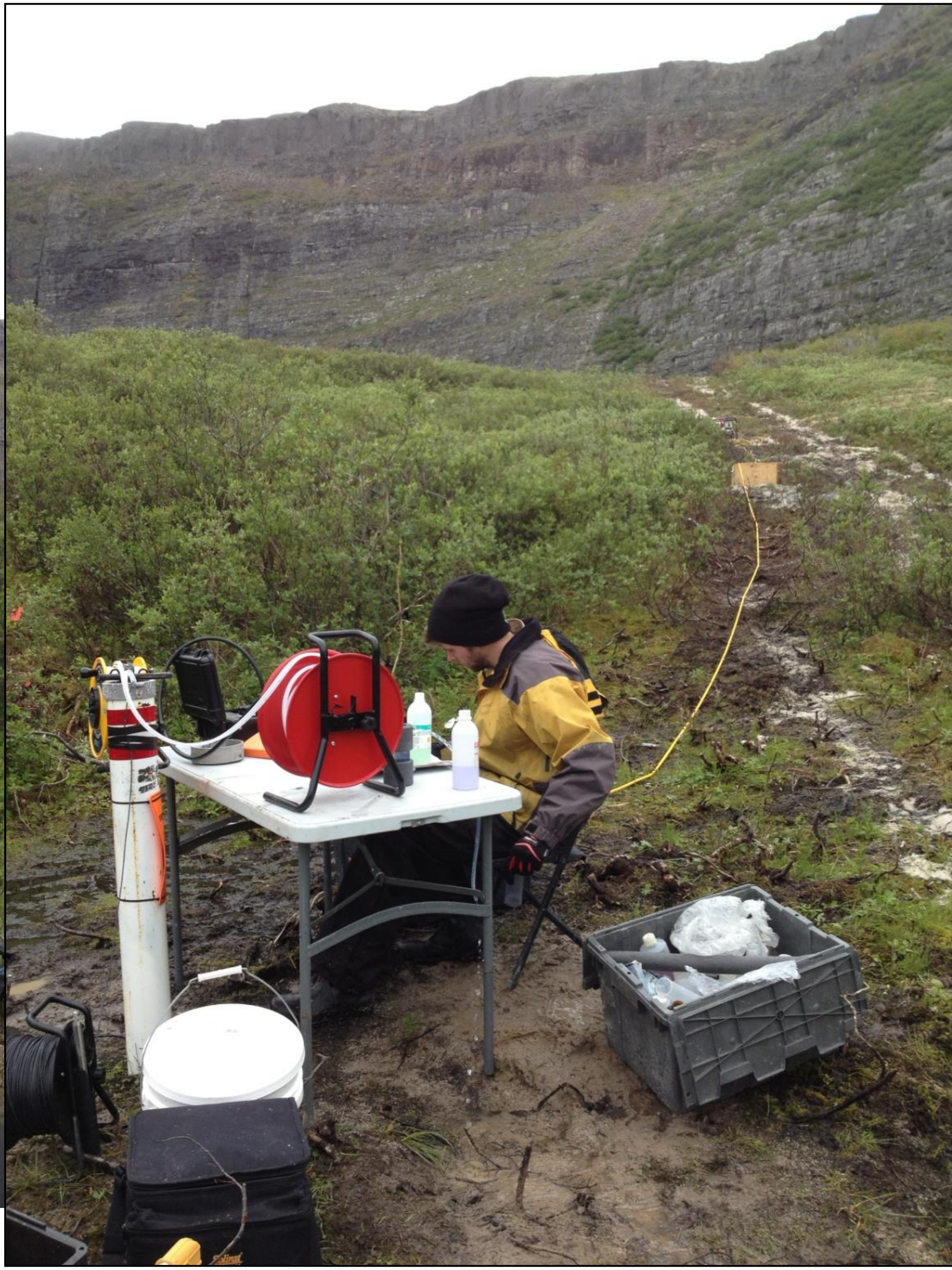
http://www.mddep.gouv.qc.ca/eau/piezo/index.htm



Airport road

Drilling campaign June 2012

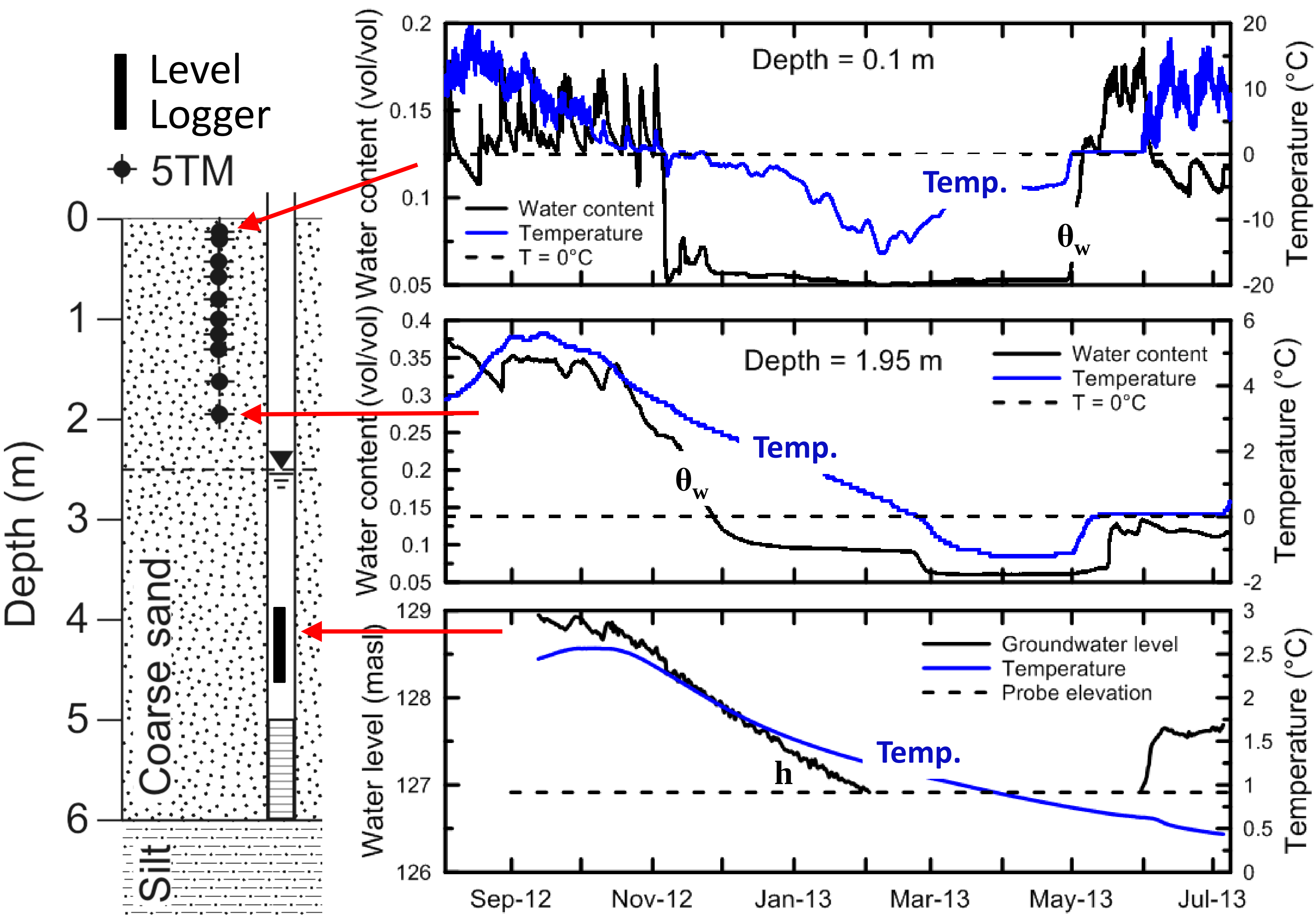
Sampling campaign July 2013



July 2013

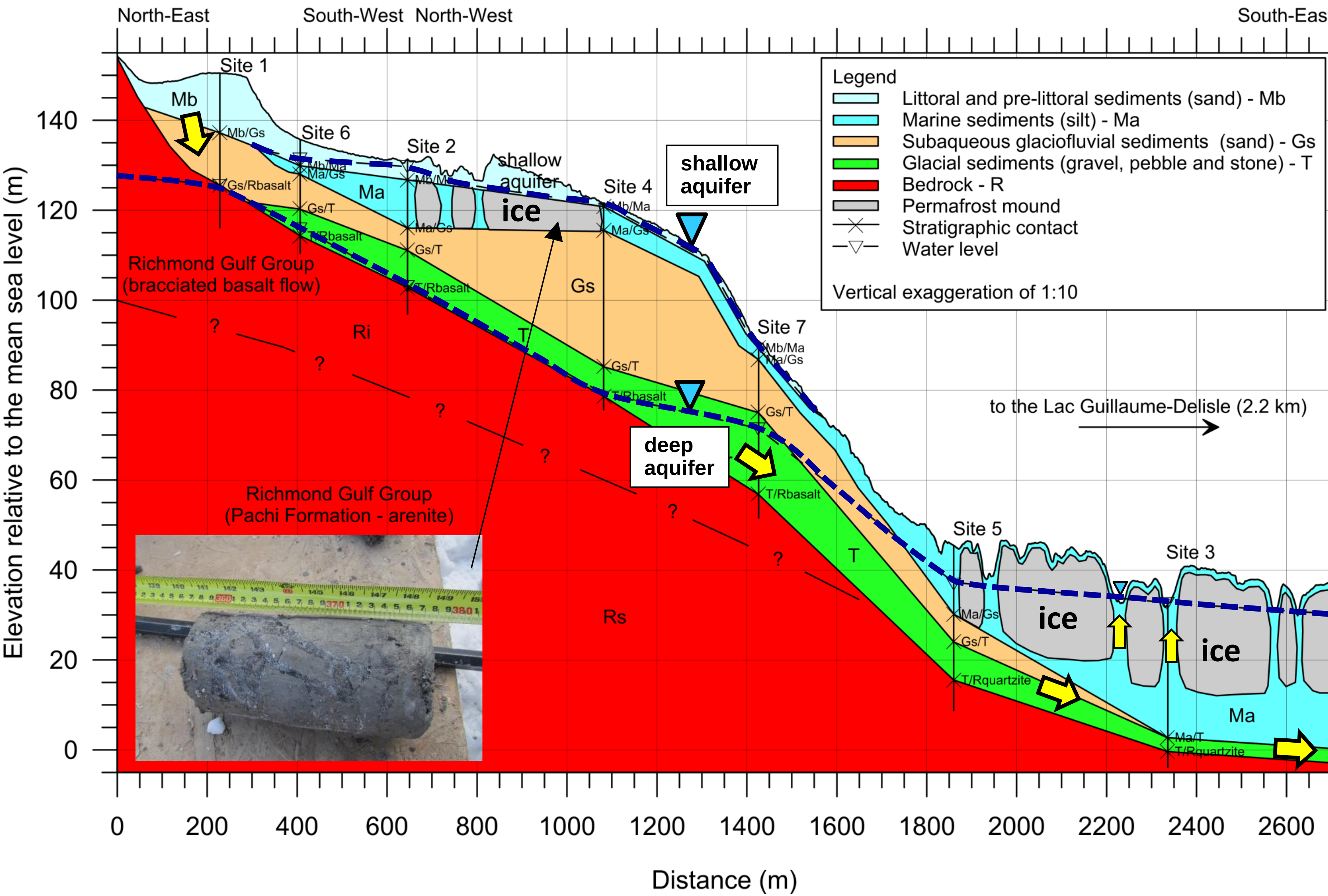

November 2014

November 2014



Level Logger
5TM
Depth (m)
0
1
2
3
4
5
6
Coarse sand
Silt
Depth = 0.1 m
Water content (vol/vol)
Temperature (°C)
Water content
Temperature
T = 0°C
Temp.
θw
Depth = 1.95 m
Water content
Temperature
T = 0°C
Temp.
θw
Water level (masl)
Temperature (°C)
Groundwater level
Temperature
Probe elevation
Temp.
h
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Time (mm-yy)

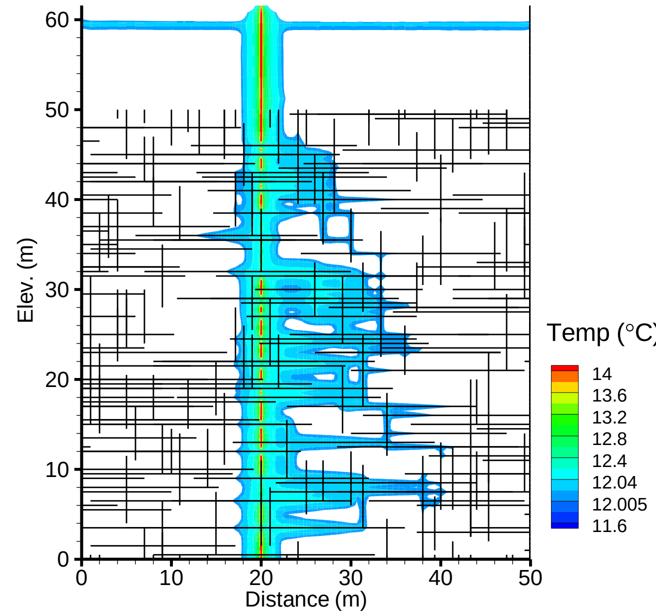
Conceptual Cross-Section



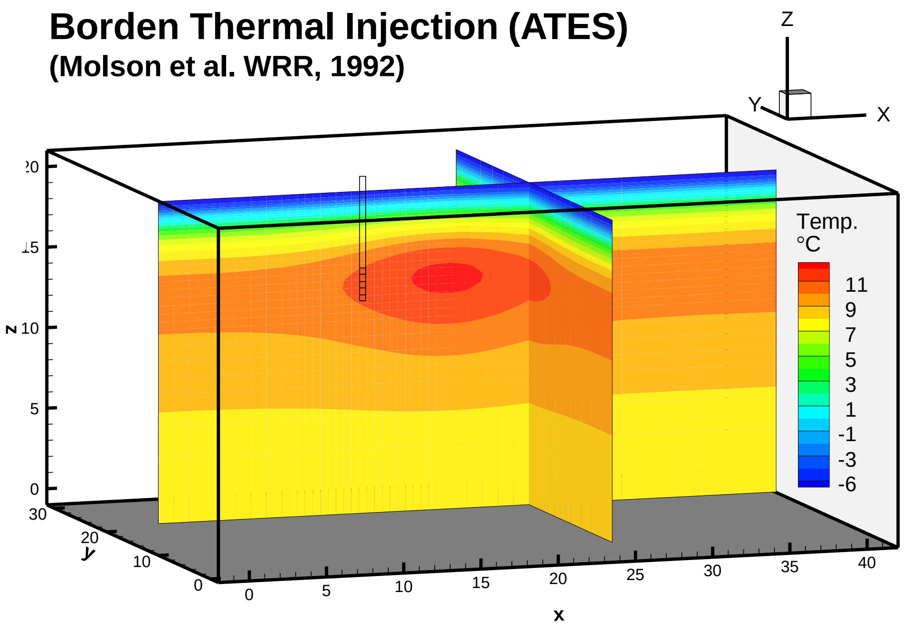
HEATFLOW/SMOKER Model
(Molson & Frind 2014)

- **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**

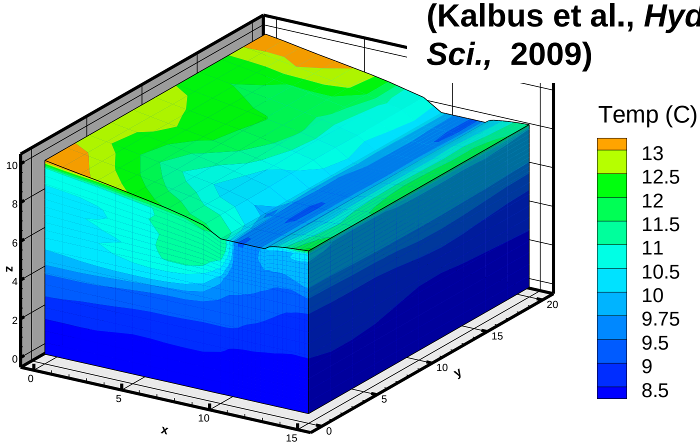
Thermal tracers: DFN
(Pehme et al., J. Hydrol. 2013)



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

Porous Matrix :

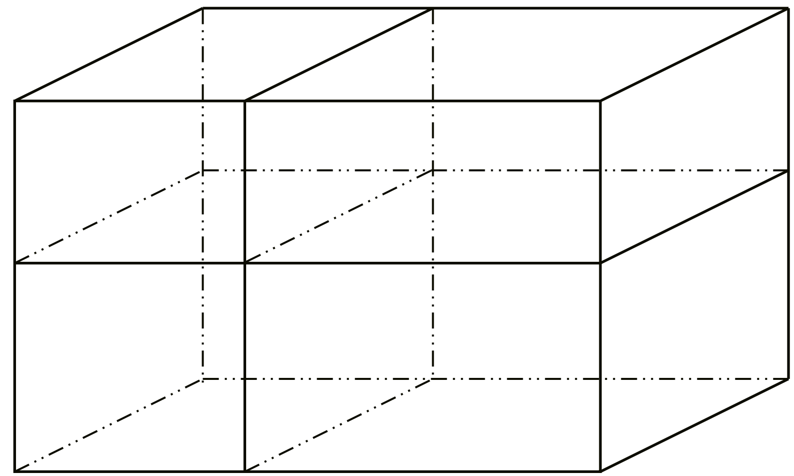
$$\frac{\partial}{\partial x_i}\left[K_{i,j}(T)\left(\frac{\partial\psi}{\partial x_j}+\rho_r(T)\cdot\bar{n}_j\right)\right] - \sum_{k=1}^{N} Q_k(t)\cdot\delta(x_k,y_k,z_k) = S_s\frac{\partial\psi}{\partial t}$$

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

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

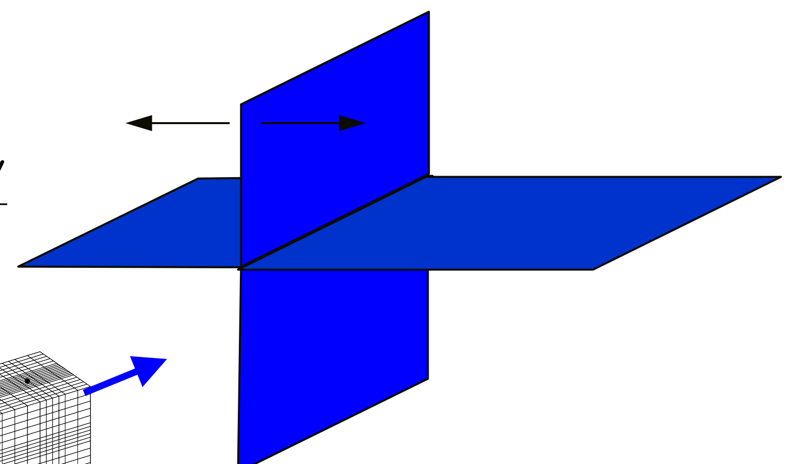
Surface b.c.:

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

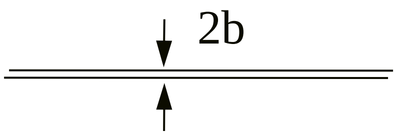


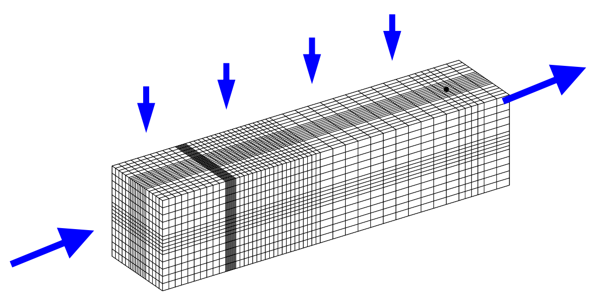
Fractures:

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

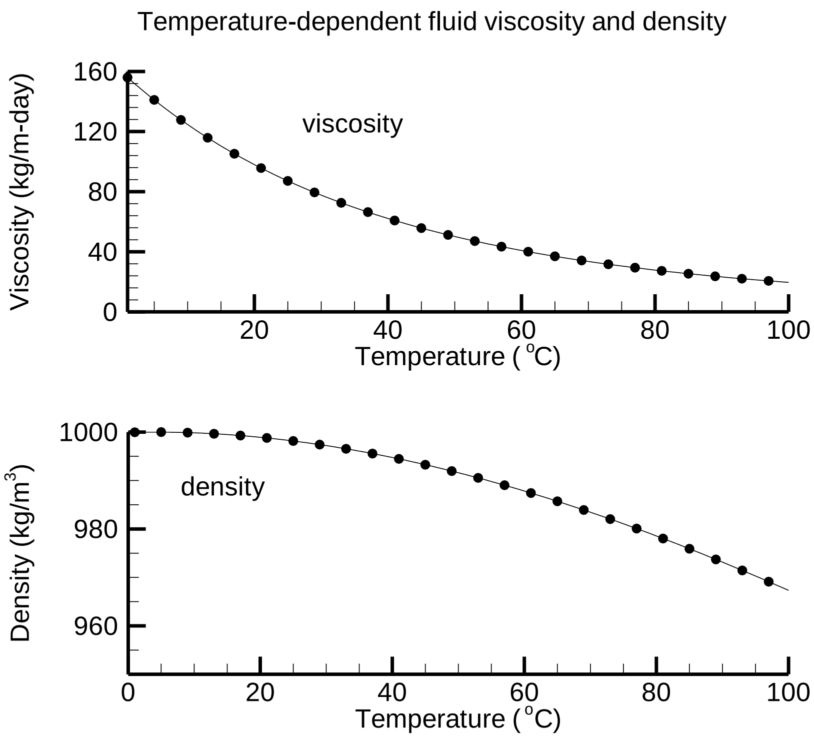


Fracture velocities: $v = \dfrac{-(2b)^2}{12\mu}\rho g\nabla h$

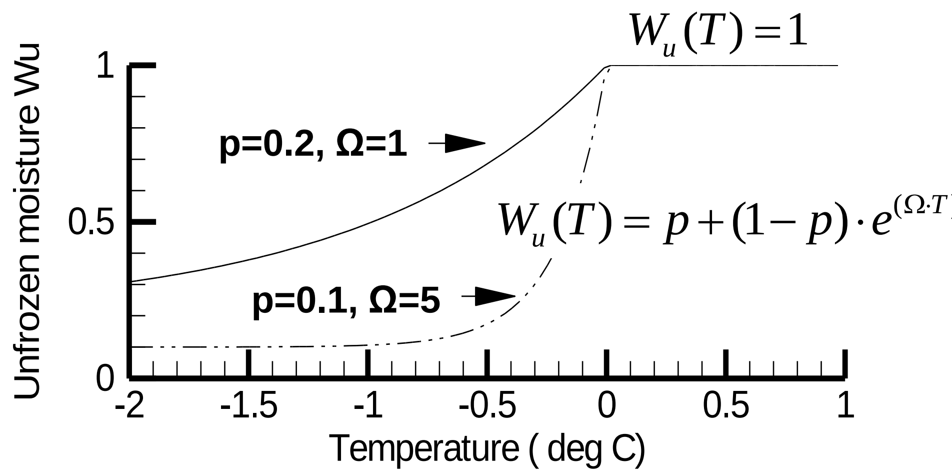




Fluid Viscosity and Density Functions:



Frozen/Unfrozen Water:



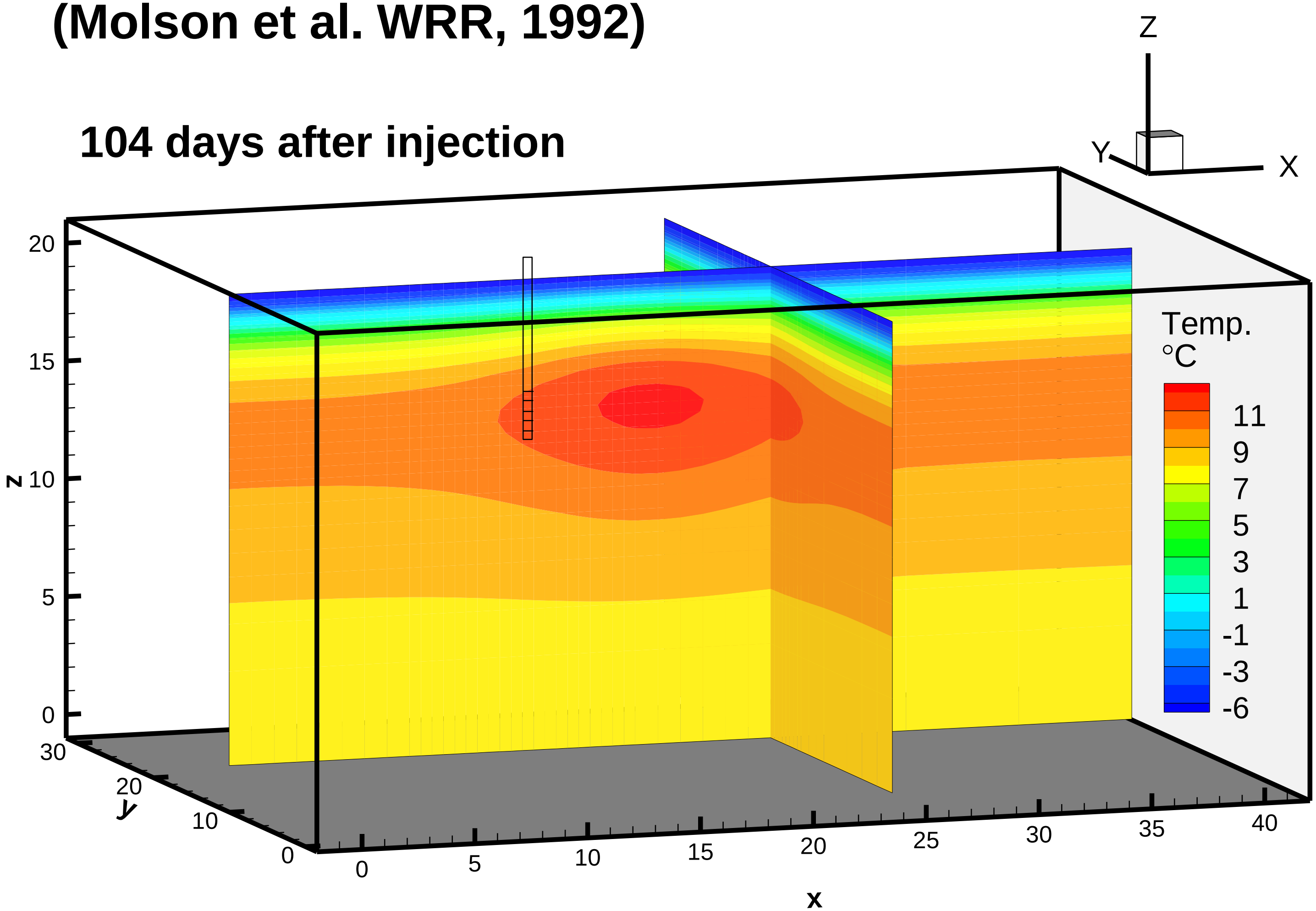
Relative Permeability k_r:

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

Borden Thermal Injection

(Molson et al. WRR, 1992)

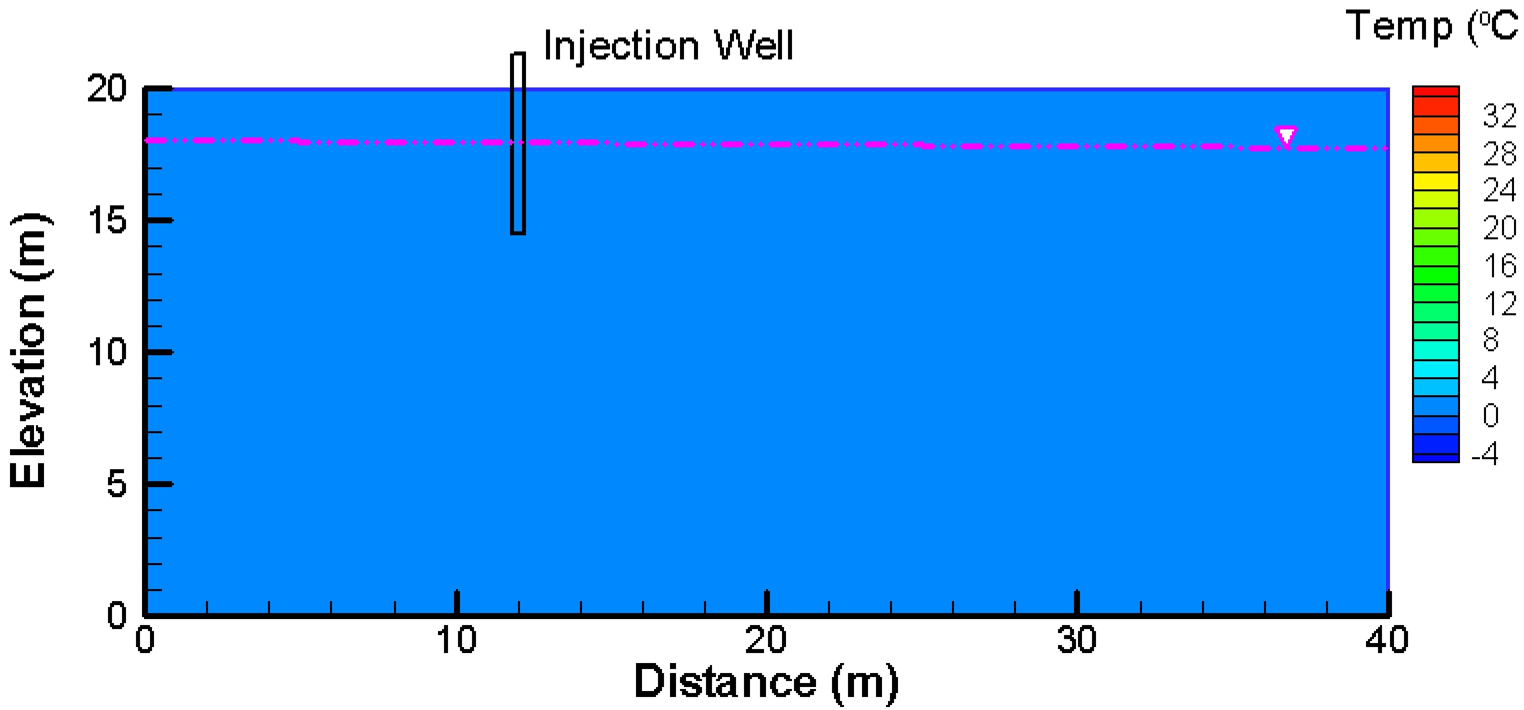
104 days after injection



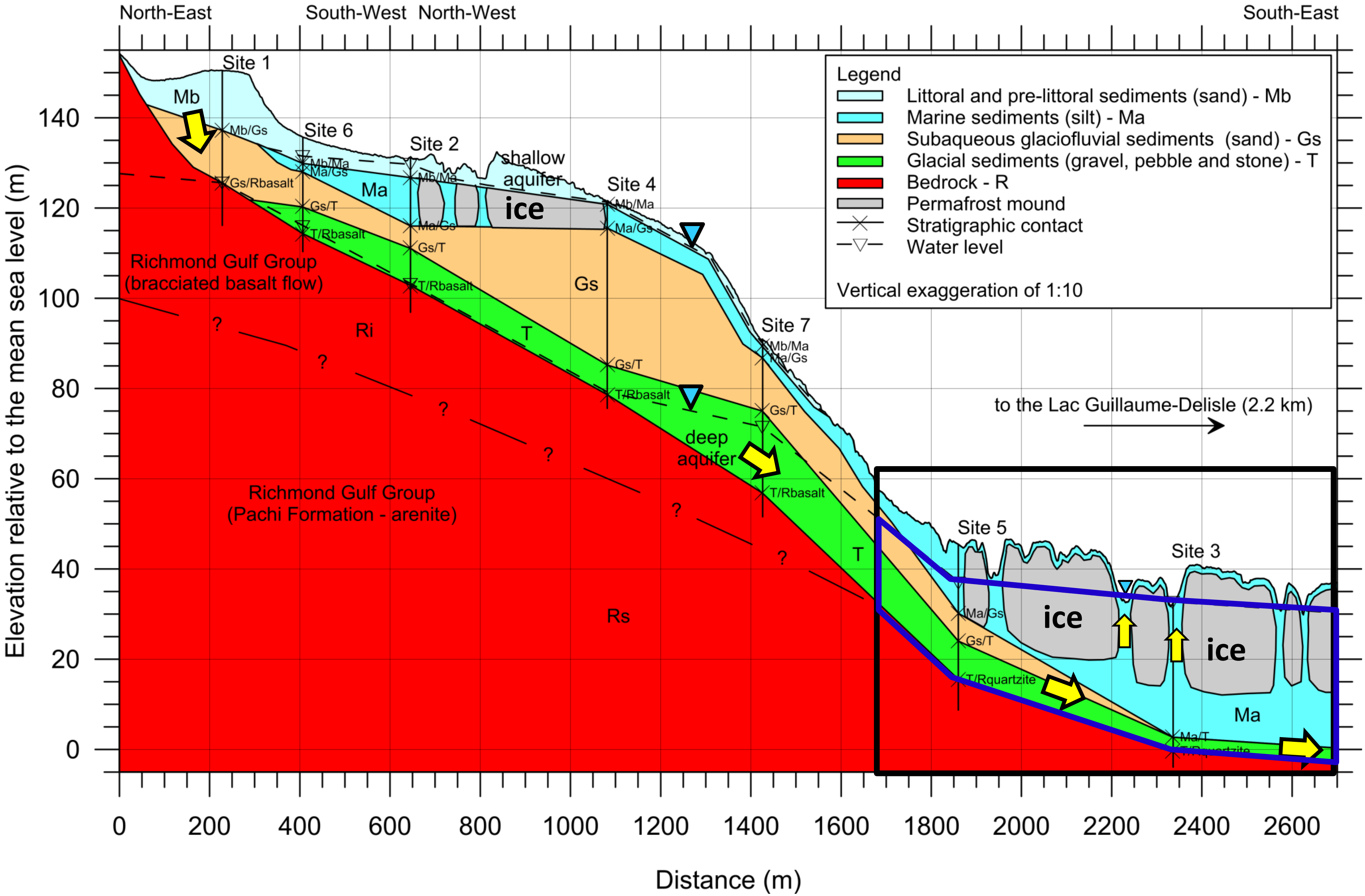
0.3 days

The Borden Thermal Injection Experiment
HEATFLOW/3D Simulation

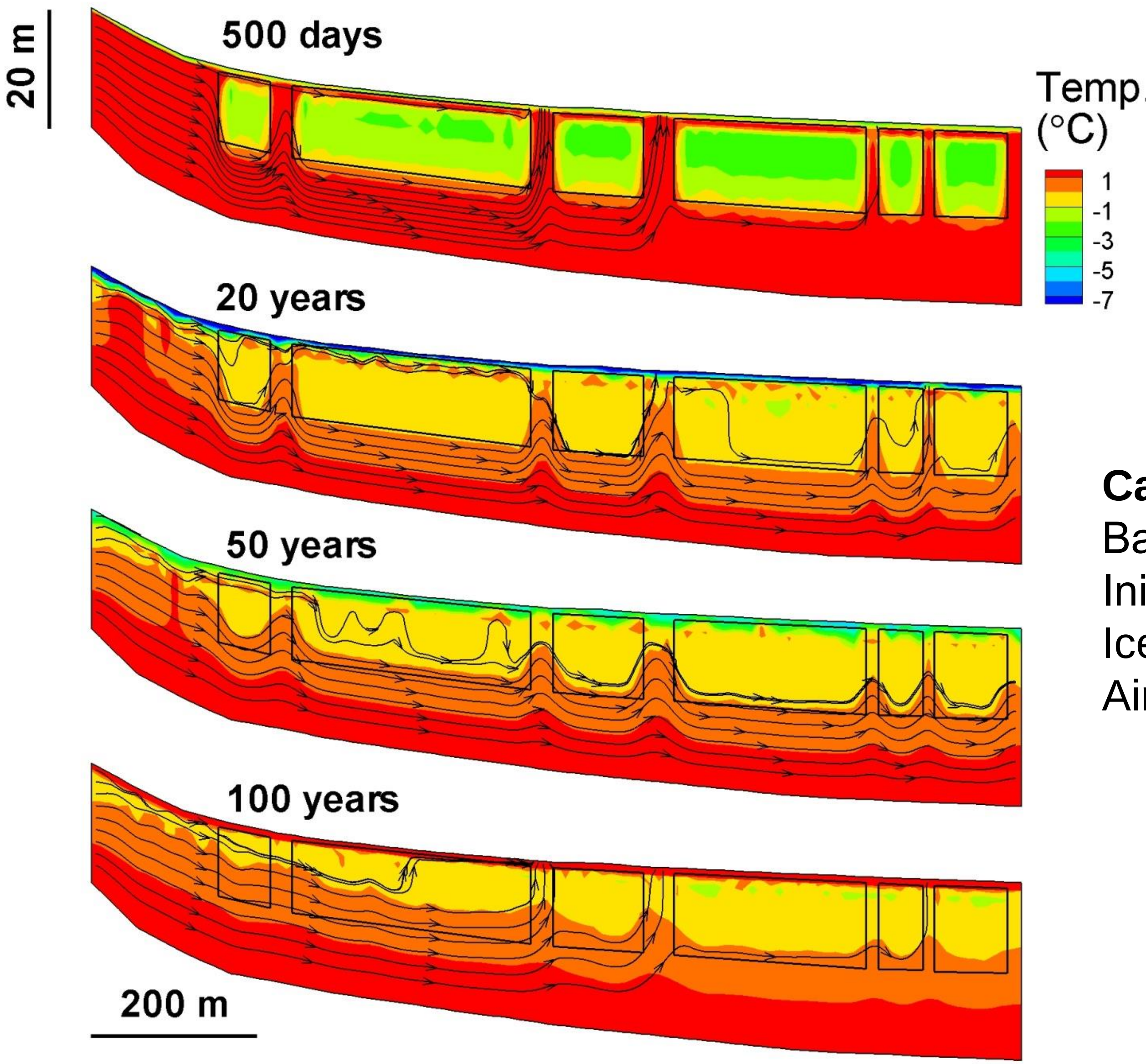
(see Molson et al., Water Resour. Res., 28 (10), 2857-2867, 1992)



Conceptual Cross-Section



Permafrost Evolution: Umiujaq
Temperature & flow lines



Case B: (warmer)

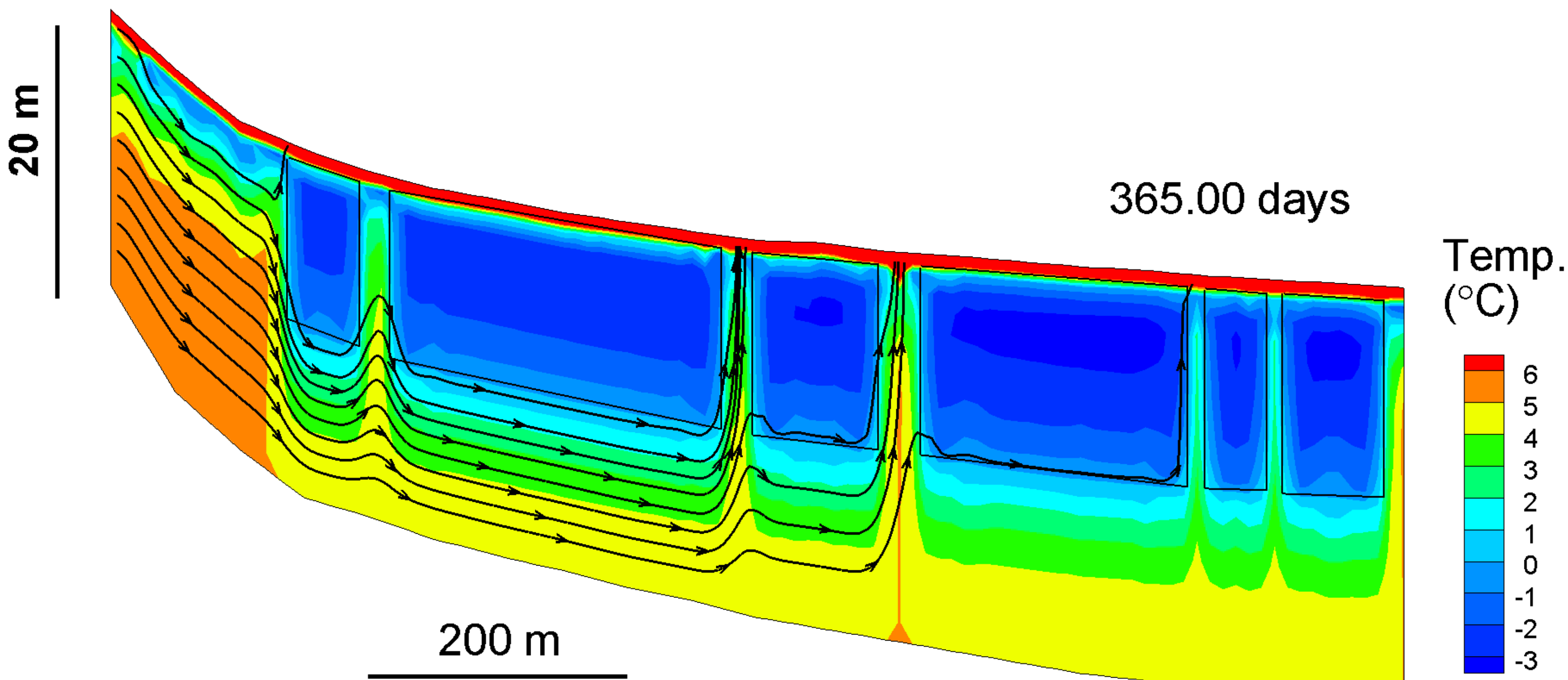
Base T= +2 ˚C

Initial T= +5 ˚C

Ice T= -5 ˚C

Air T_{min}= -20, A= +25 ˚C

Permafrost Evolution: Umiujaq
Temperature & flow lines



Acknowledgements

Développement durable, Environnement et Lutte contre les changements climatiques

Québec

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

NSERC CRSNG

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

Fonds de recherche Nature et technologies

Québec

Centre d'études nordiques

Université Laval

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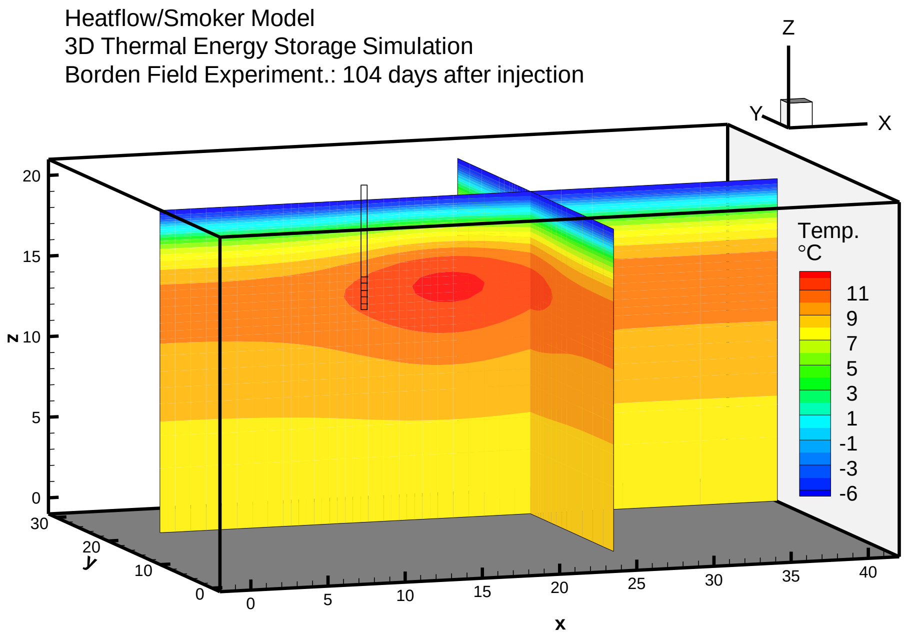
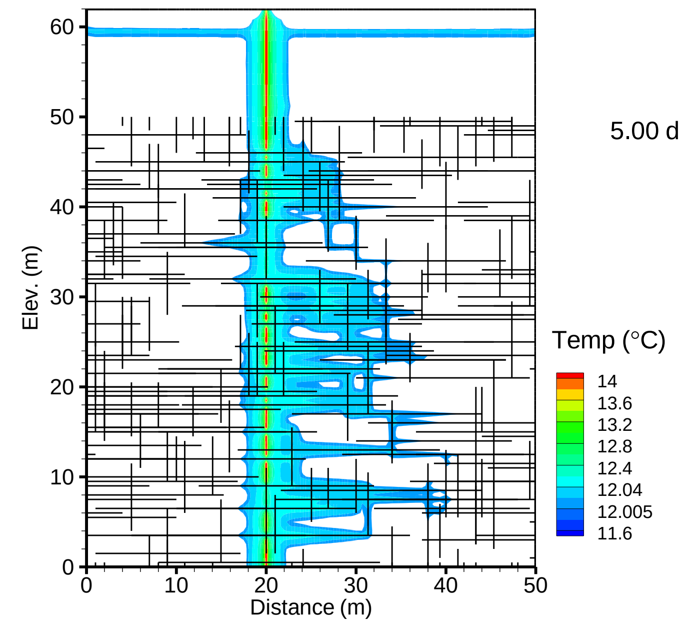
Program of Energy Research and Development (PERD)

Indian & Northern Affairs Canada (INAC)

Model Benchmarks

HEATFLOW/SMOKER Model





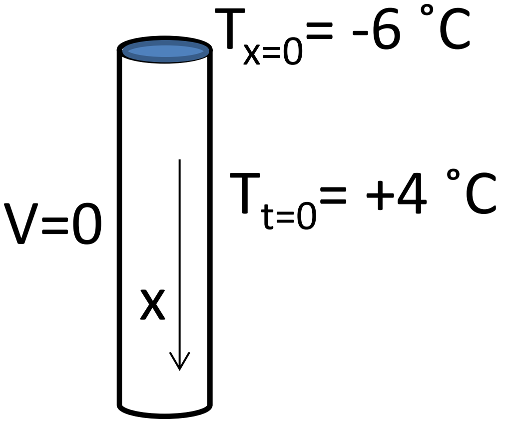
Model Benchmarks:

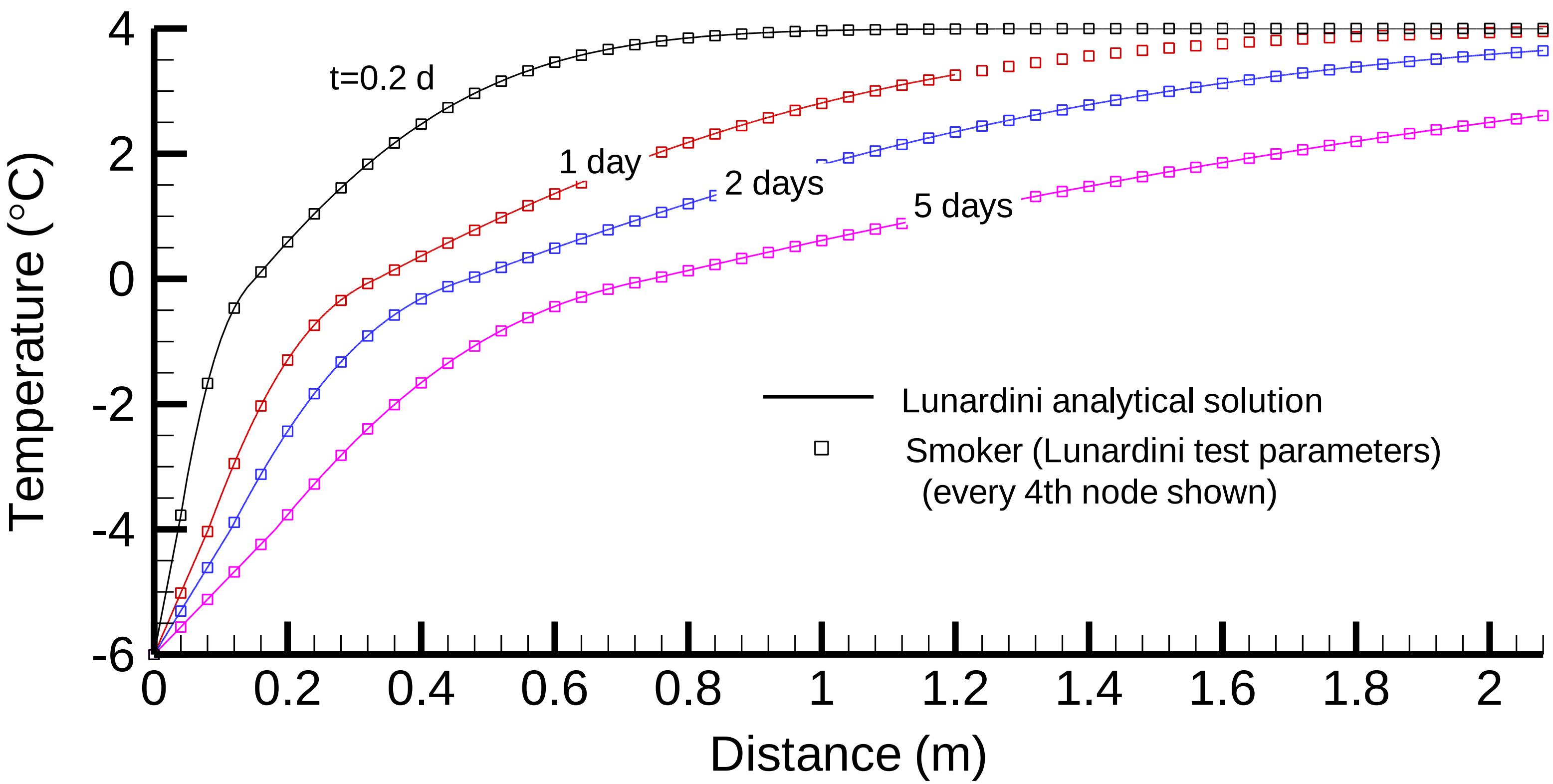
HEATFLOW/SMOKER Model

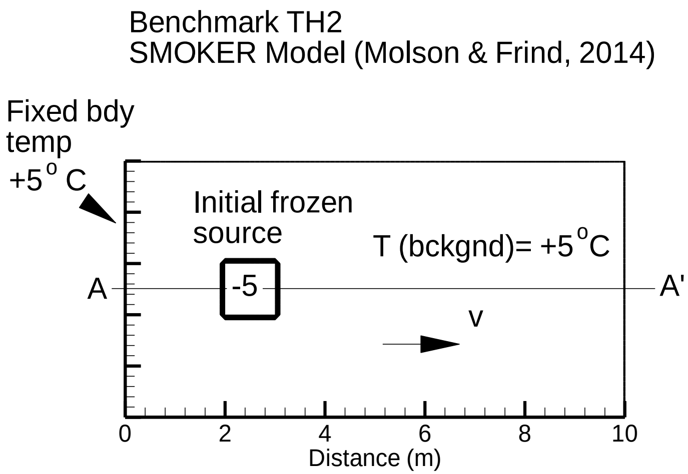
Validation:

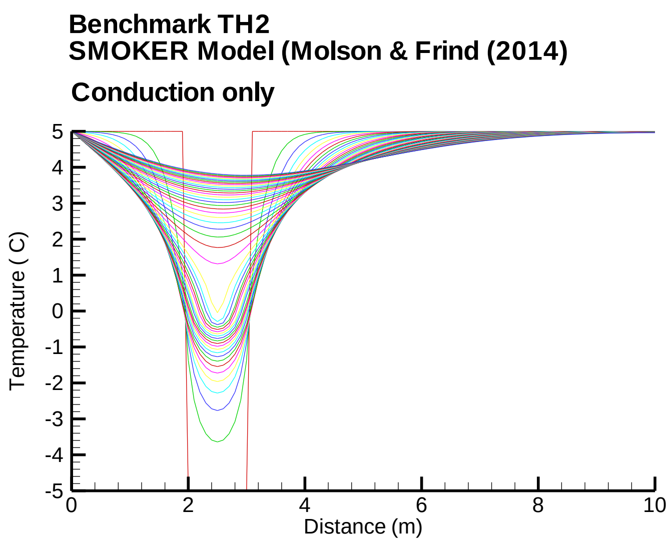
Lunardini (1985) 3-zone solution

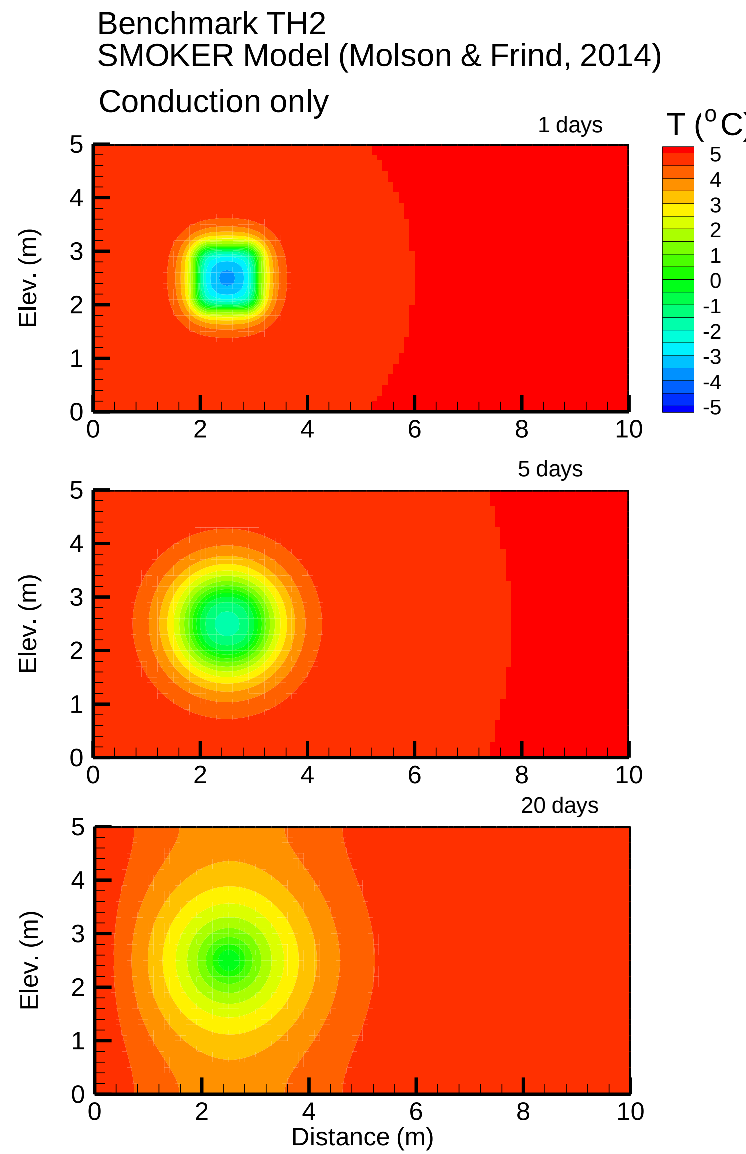
programmed by M. Ghias, U. Laval

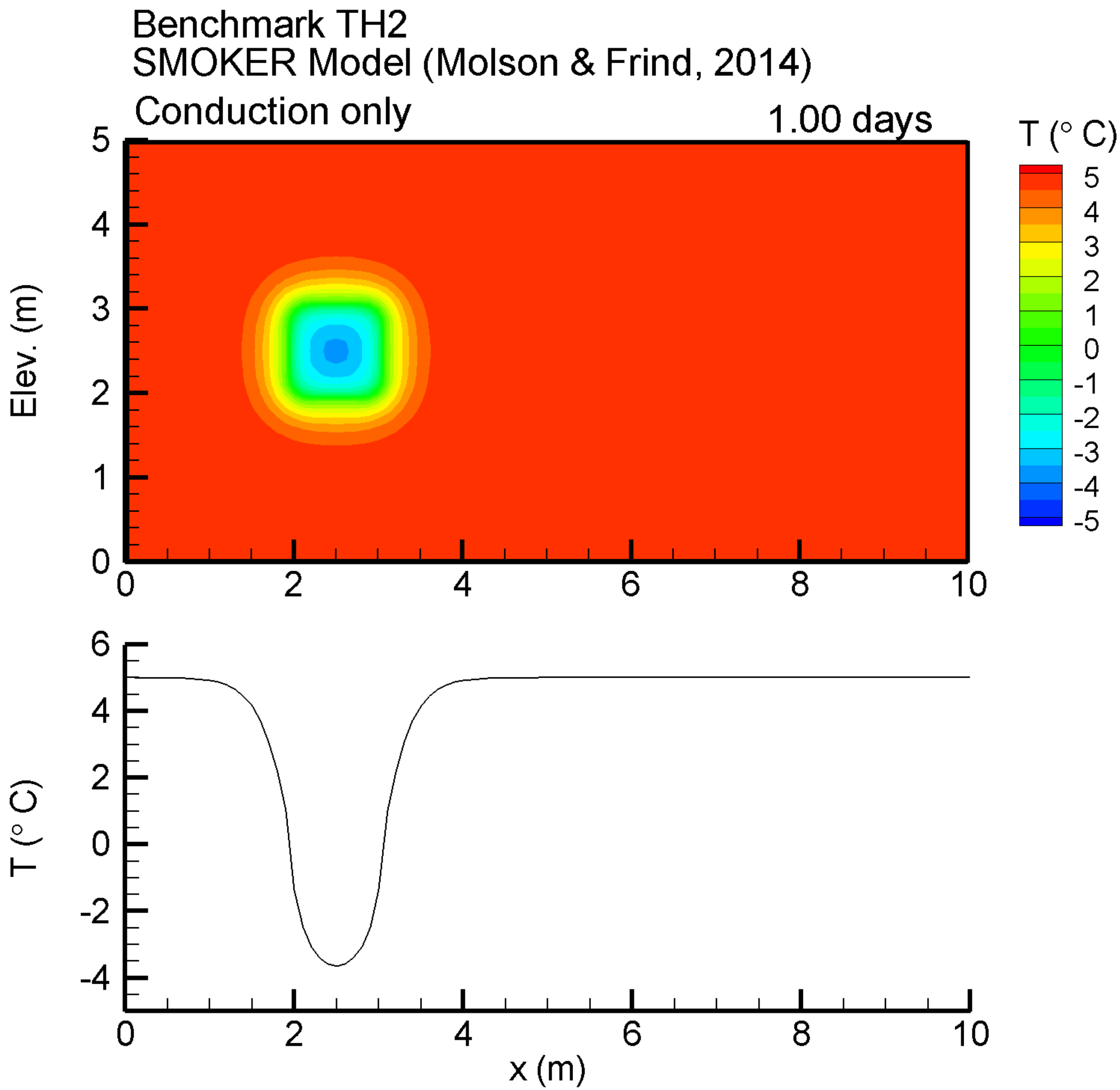


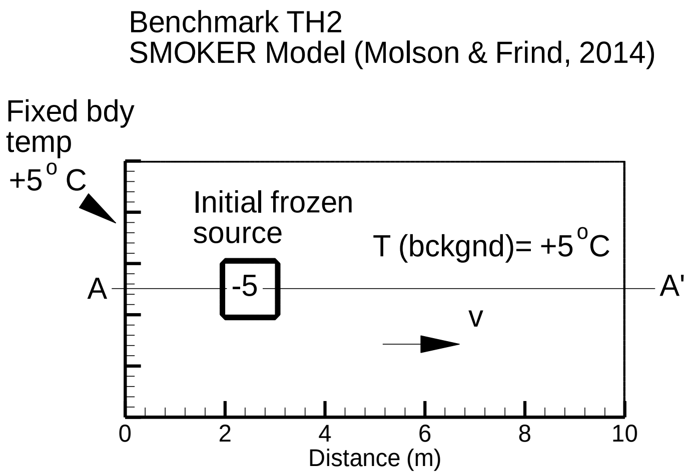


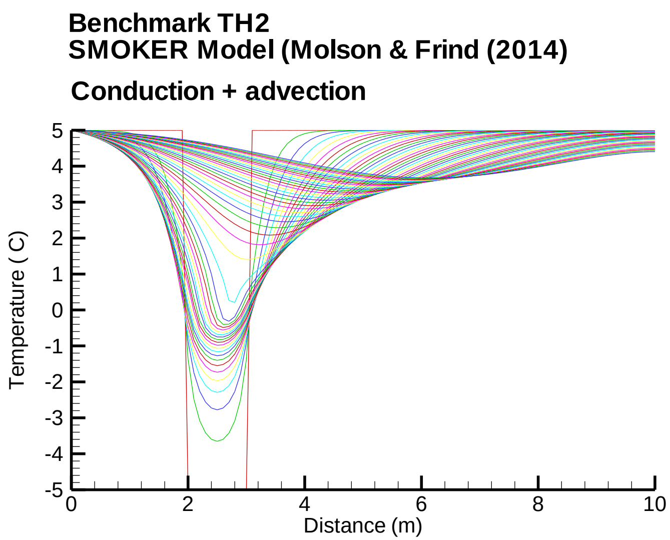

Benchmark TH2
SMOKER Model (Molson & Frind, 2014)
Fixed bdy
temp
+5 o C
Initial frozen
source
-5
T (bckgnd)= +5 oC
A
A'
v
0
2
4
6
8
10
Distance (m)

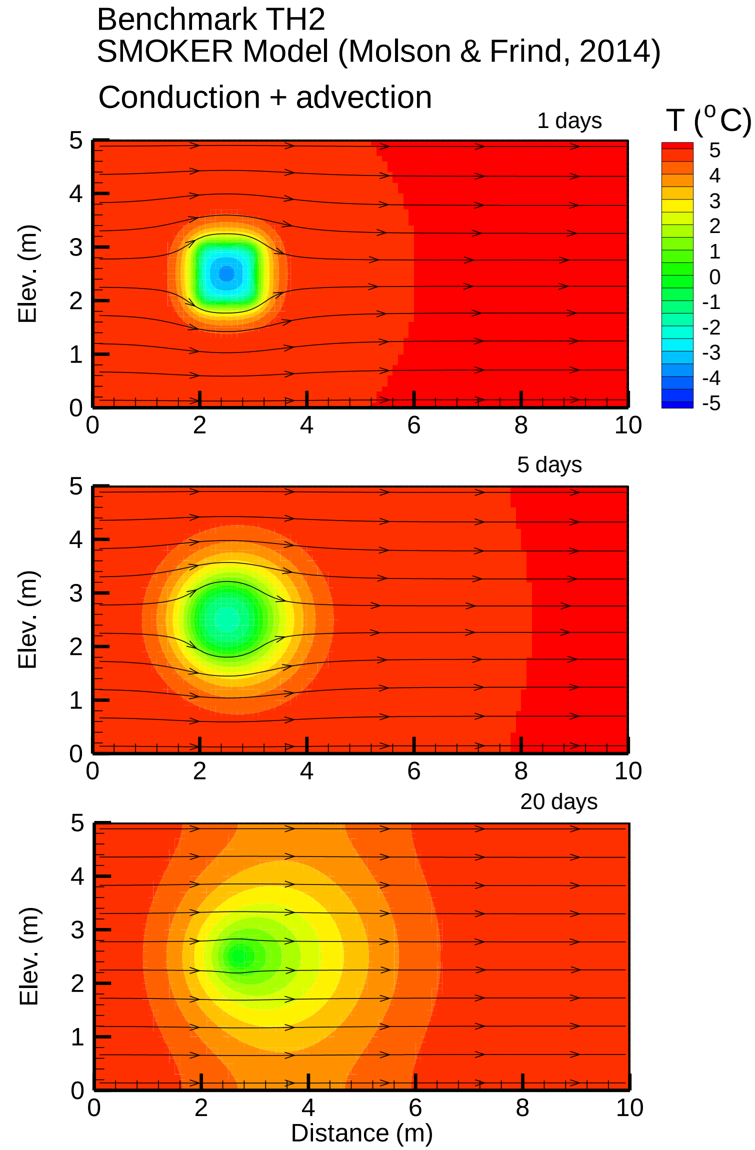

Benchmark TH2
SMOKER Model (Molson & Frind (2014)
Conduction only
Temperature (C)
5
4
3
2
1
0
-1
-2
-3
-4
-5
0
2
4
6
8
10
Distance (m)

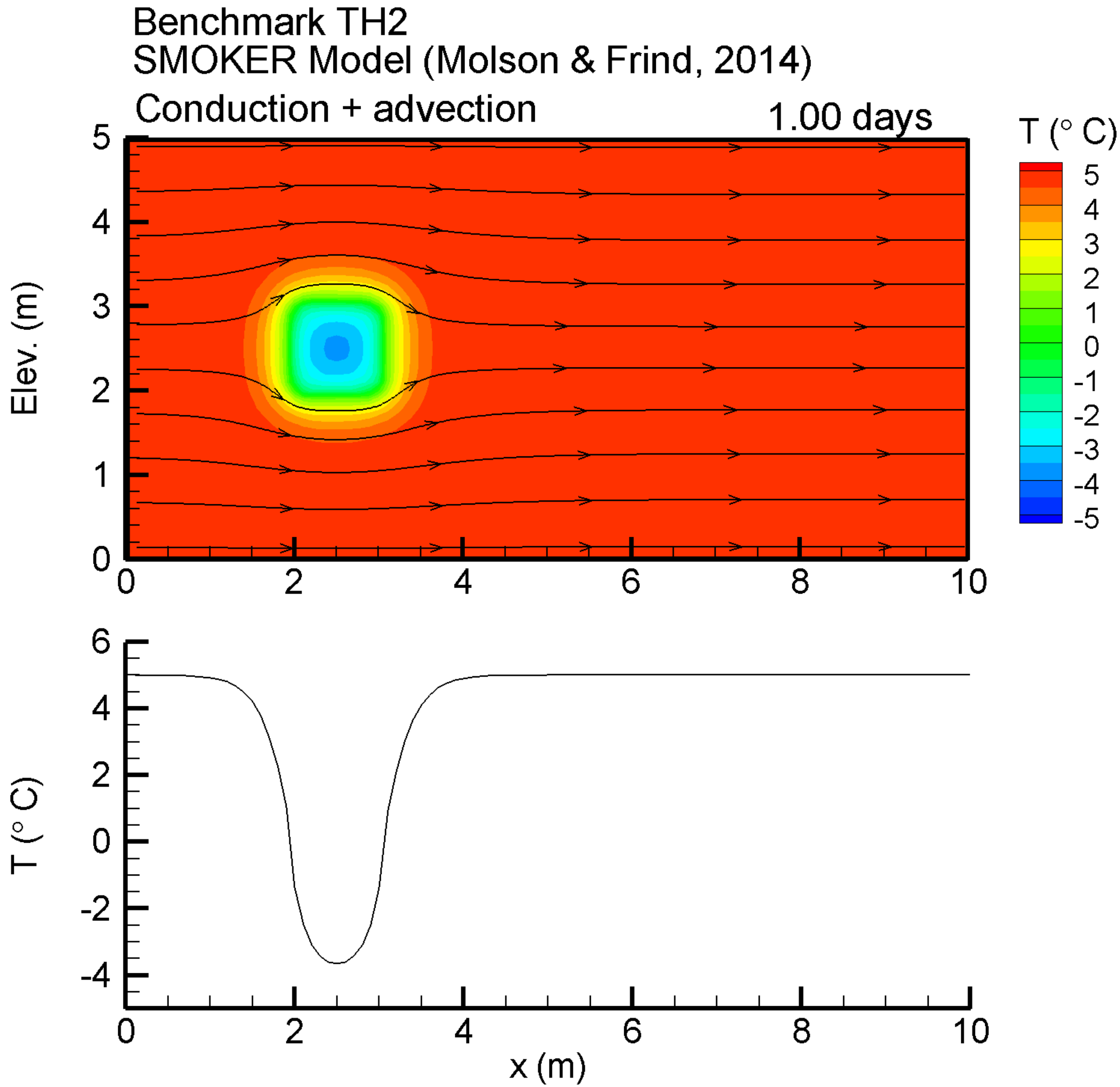

Benchmark TH2
SMOKER Model (Molson & Frind, 2014)
Conduction only
1 days
5 days
20 days
T (oC)
5
4
3
2
1
0
-1
-2
-3
-4
-5
Elev. (m)
0
1
2
3
4
5
0
2
4
6
8
10
Distance (m)

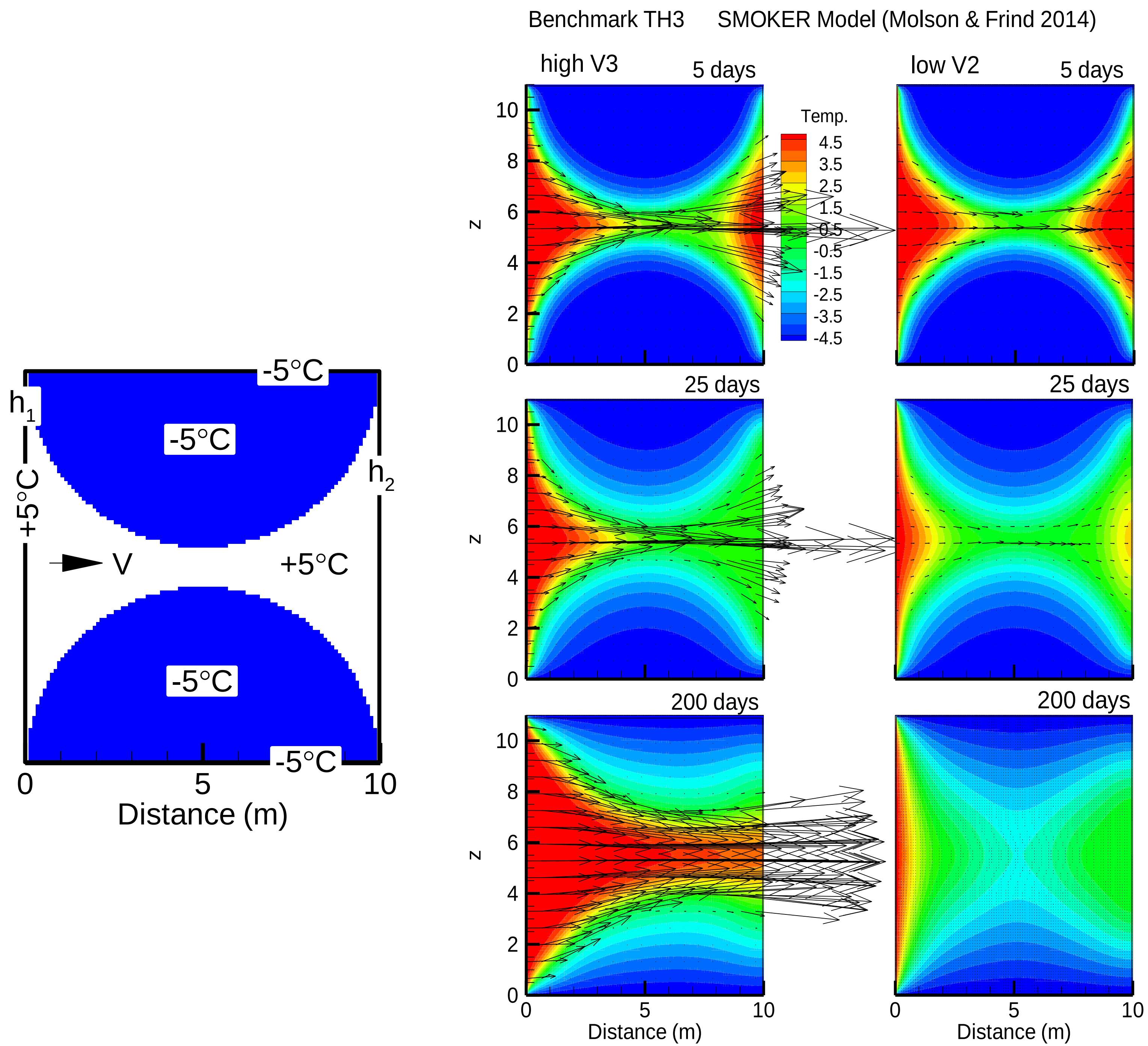

Benchmark TH2
SMOKER Model (Molson & Frind, 2014)
Conduction only
1.00 days
T (° C)
5
4
3
2
1
0
-1
-2
-3
-4
-5
Elev. (m)
0
1
2
3
4
5
0
2
4
6
8
10
T (° C)
6
4
2
0
-2
-4
0
2
4
6
8
10
x (m)


Benchmark TH2
SMOKER Model (Molson & Frind, 2014)
Fixed bdy temp +5 °C
Initial frozen source
-5
T (bckgnd)= +5 °C
A
A'
v
0
2
4
6
8
10
Distance (m)

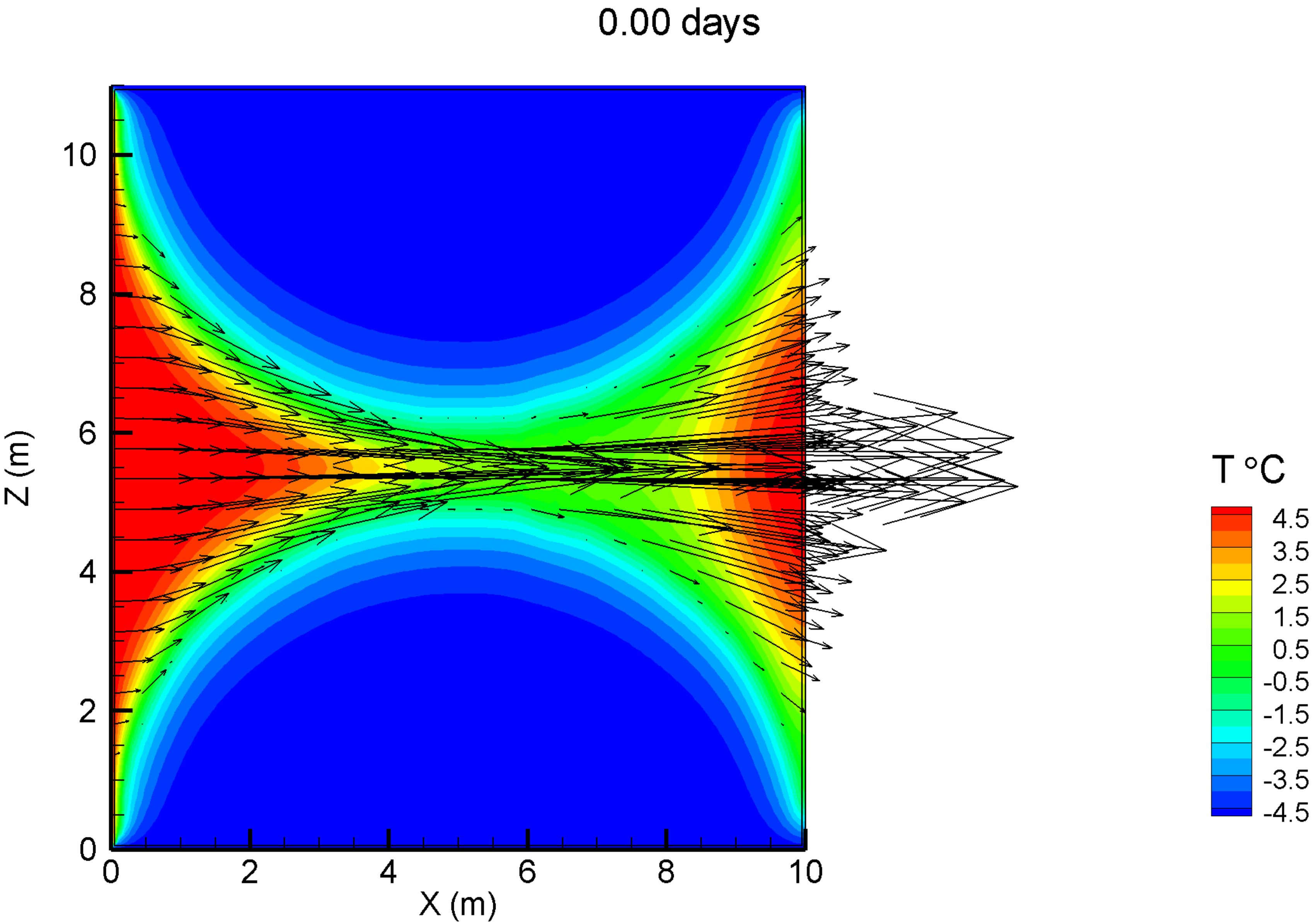

Benchmark TH2
SMOKER Model (Molson & Frind (2014)
Conduction + advection
Temperature (C)
5
4
3
2
1
0
-1
-2
-3
-4
-5
0
2
4
6
8
10
Distance (m)

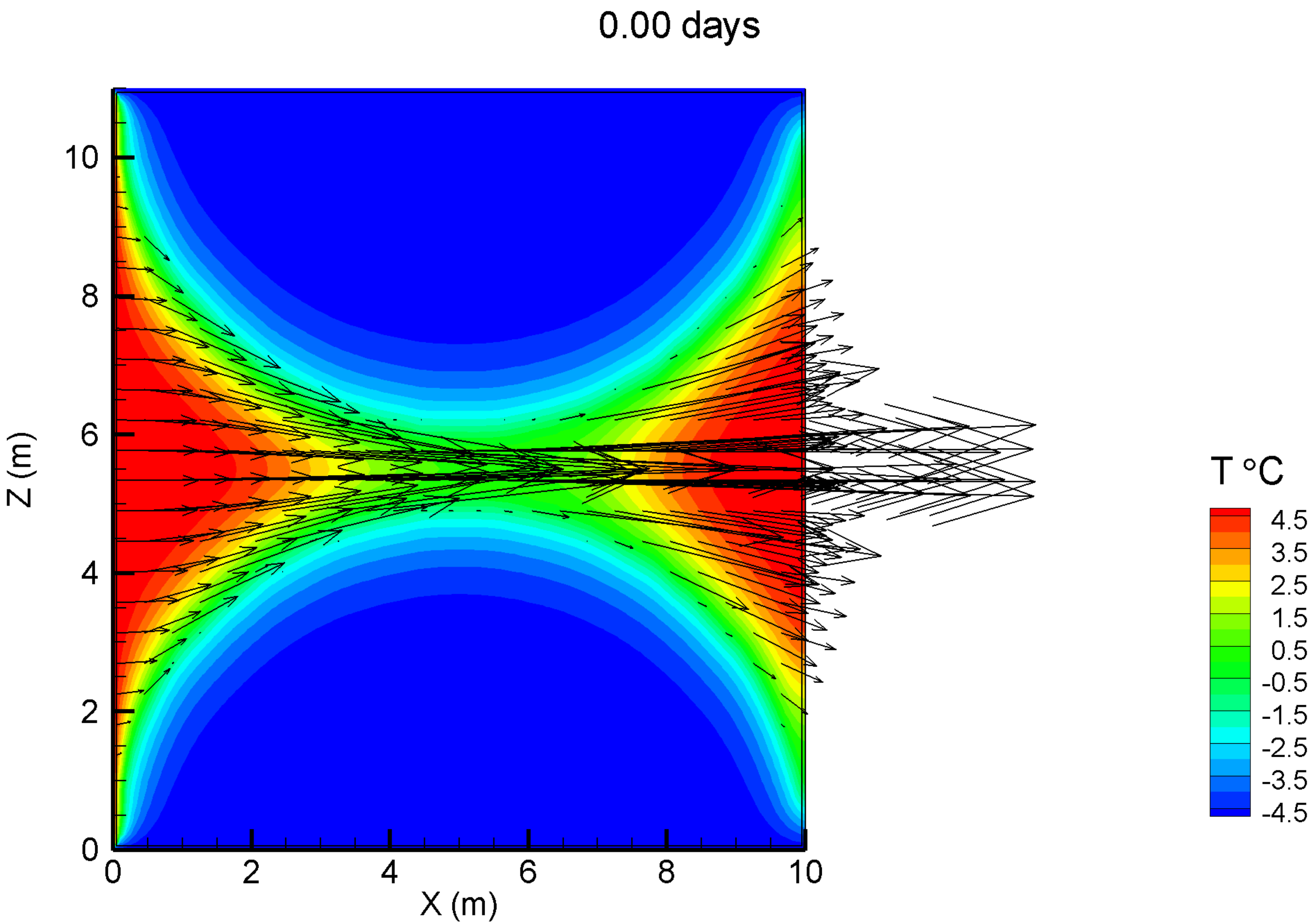

Benchmark TH2
SMOKER Model (Molson & Frind, 2014)
Conduction + advection
1 days
5 days
20 days
T (°C)
5
4
3
2
1
0
-1
-2
-3
-4
-5
Elev. (m)
Distance (m)


Benchmark TH2
SMOKER Model (Molson & Frind, 2014)
Conduction + advection
1.00 days
T (° C)
5
4
3
2
1
0
-1
-2
-3
-4
-5
Elev. (m)
T (° C)
x (m)



Benchmark TH3
SMOKER Model (Molson & Frind 2014)
high V3
low V2
5 days
25 days
200 days
Temp.
4.5
3.5
2.5
1.5
0.5
-0.5
-1.5
-2.5
-3.5
-4.5
z
Distance (m)
-5°C
+5°C
V
h1
h2


0.00 days
Z (m)
X (m)
T °C
4.5
3.5
2.5
1.5
0.5
-0.5
-1.5
-2.5
-3.5
-4.5
0
2
4
6
8
10


0.00 days
Z (m)
X (m)
0
2
4
6
8
10
T °C
4.5
3.5
2.5
1.5
0.5
-0.5
-1.5
-2.5
-3.5
-4.5

Acknowledgements

Développement durable, Environnement et Lutte contre les changements climatiques

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UNIVERSITÉ LAVAL

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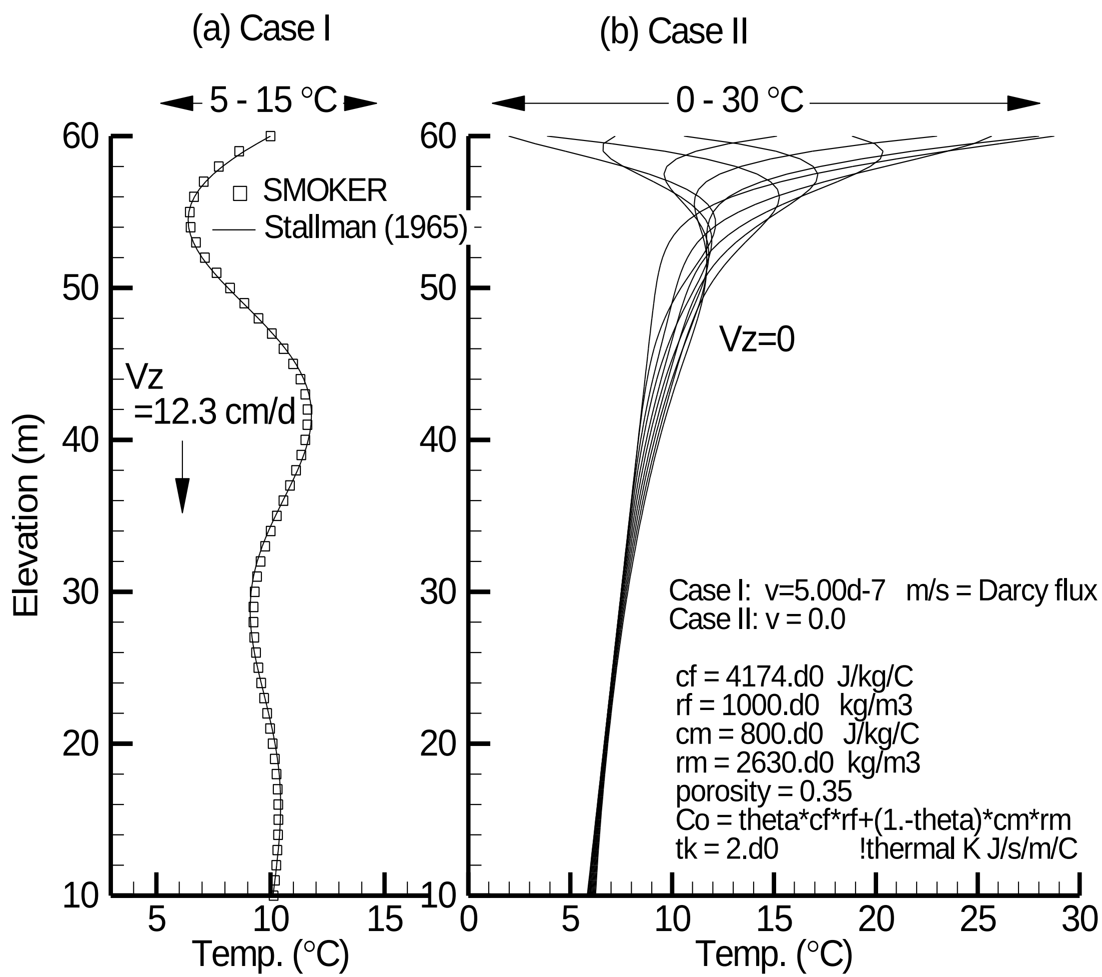
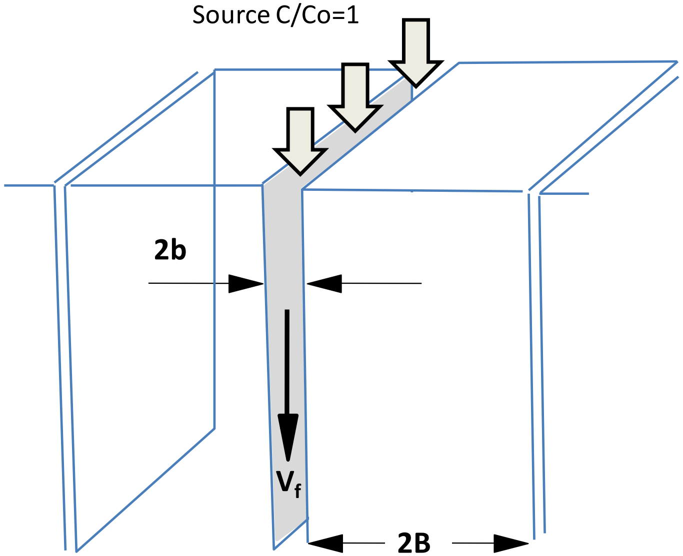
Program of Energy Research and Development (PERD)

Indian & Northern Affairs Canada (INAC)

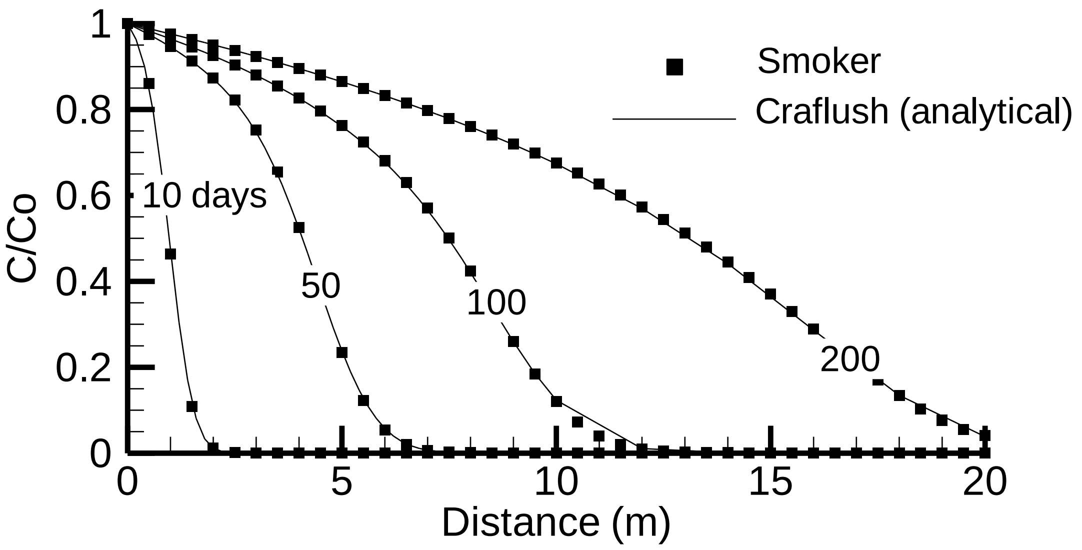
Validation: Stallman (1965) Solution



Validation: Discrete Fractures

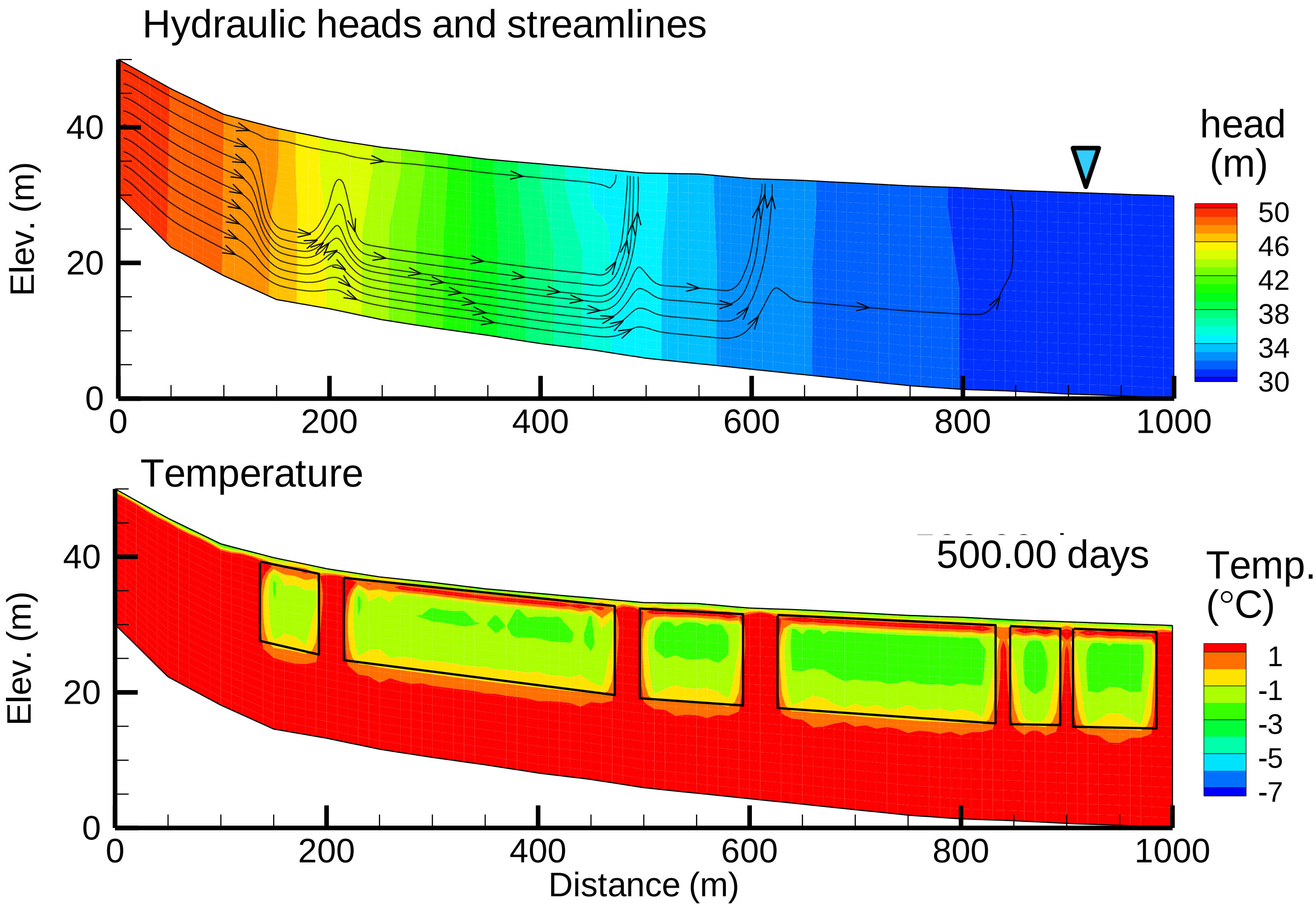


Craflush vs. Smoker
1D mass transport, single fracture

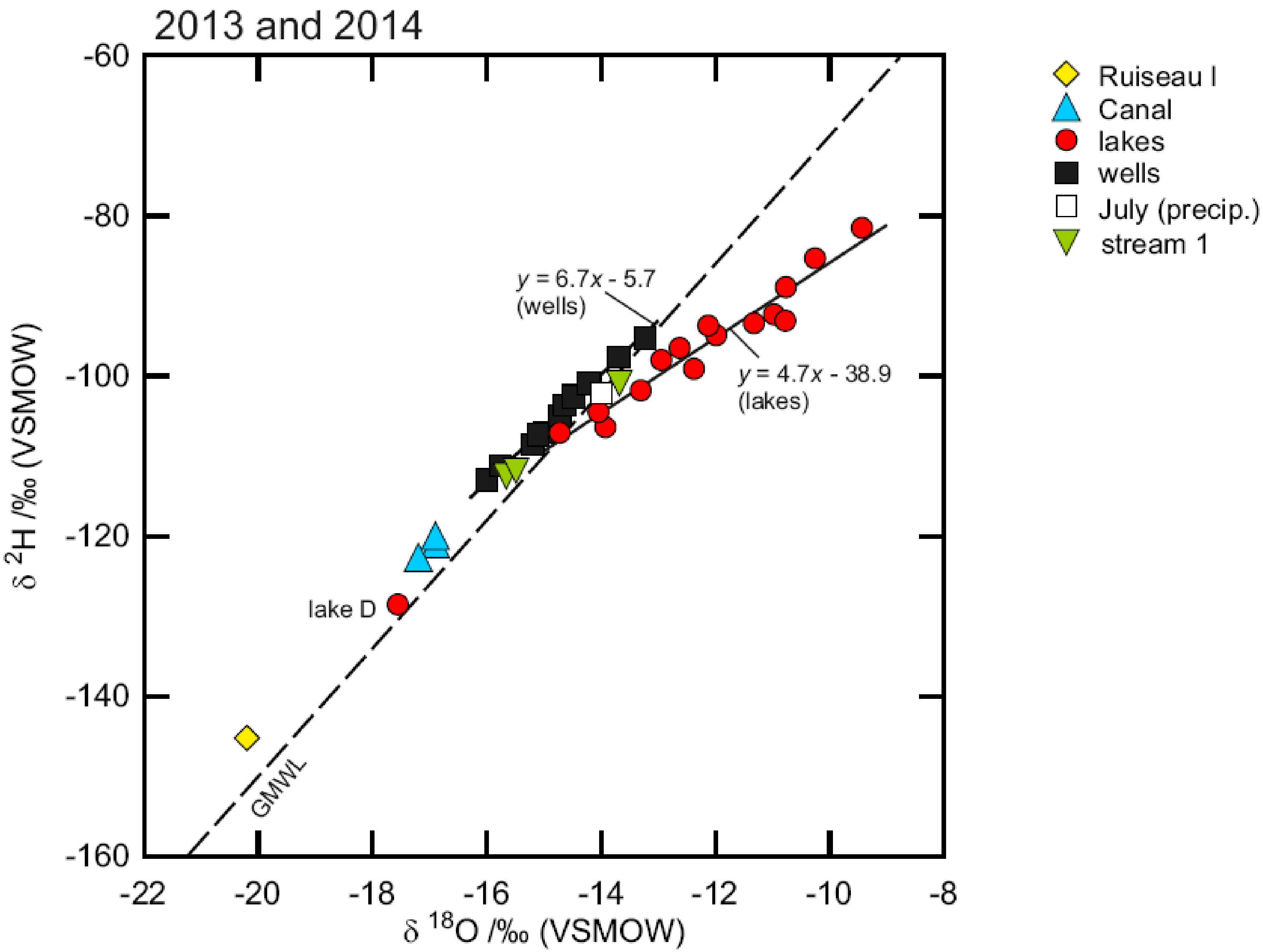


Umiujaq Model: Permafrost Hydrogeology

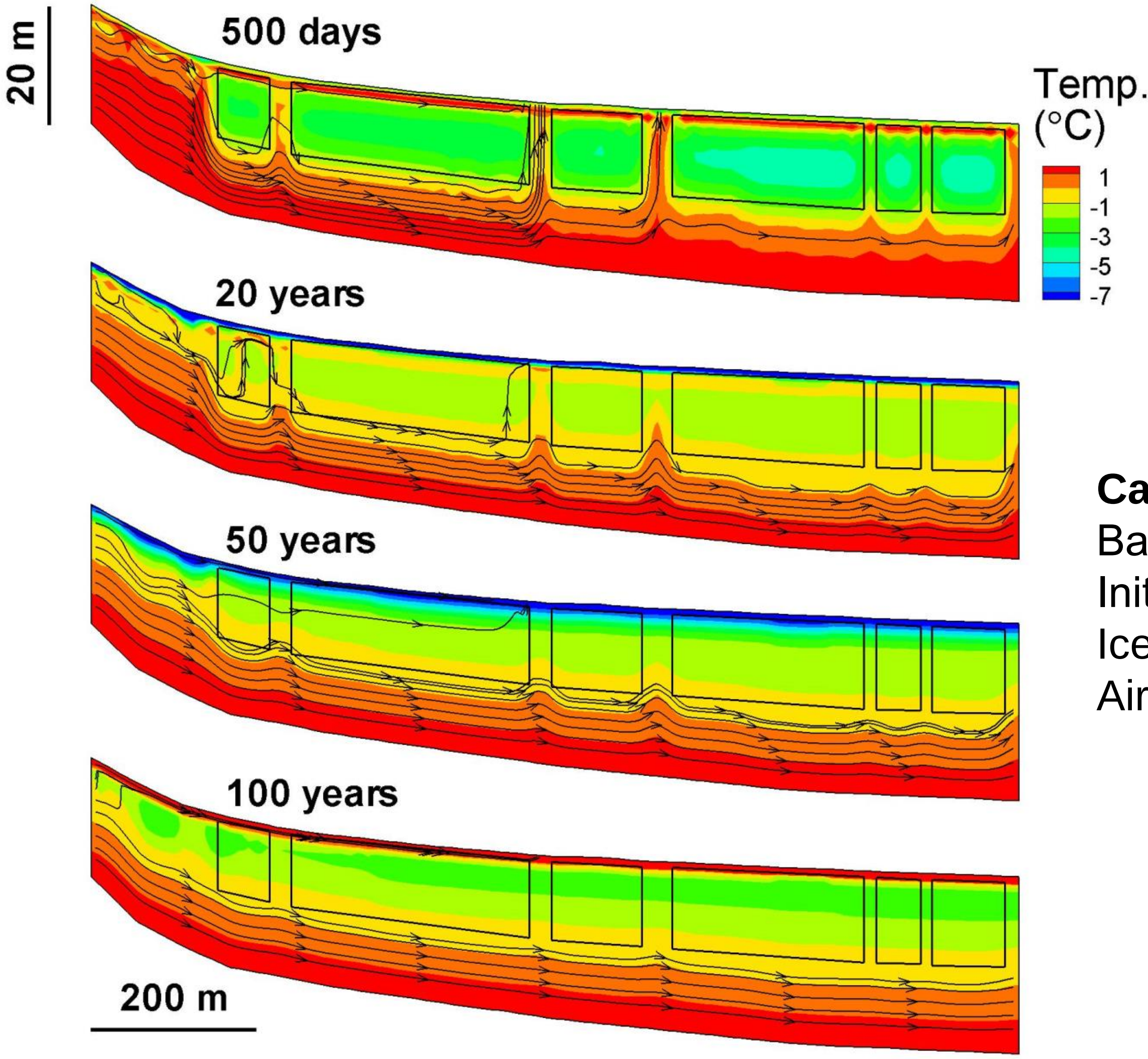
HEATFLOW/SMOKER Model



Umiujaq Isotope Data 2013-2014



Permafrost Evolution: Umiujaq
Temperature & flow lines

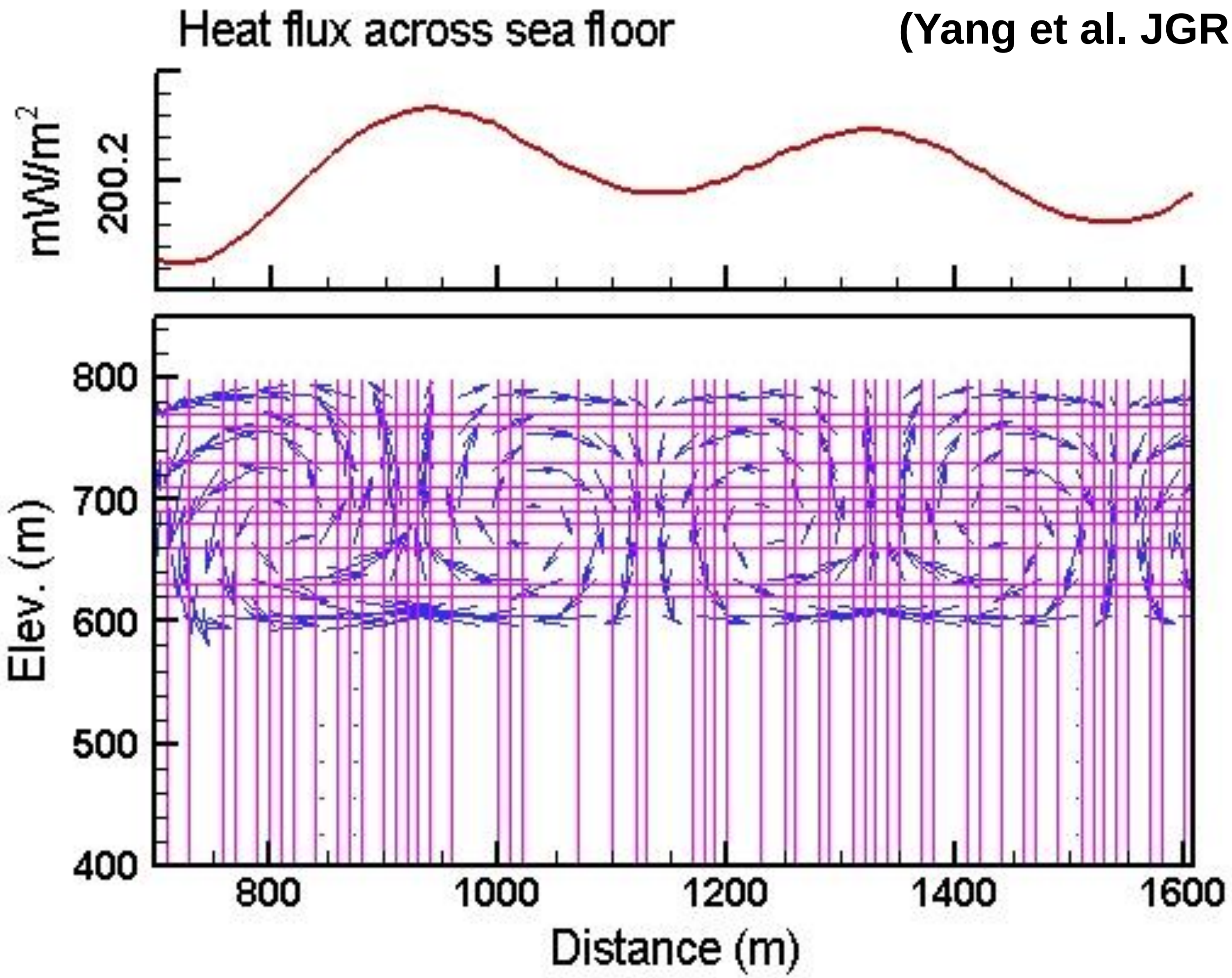


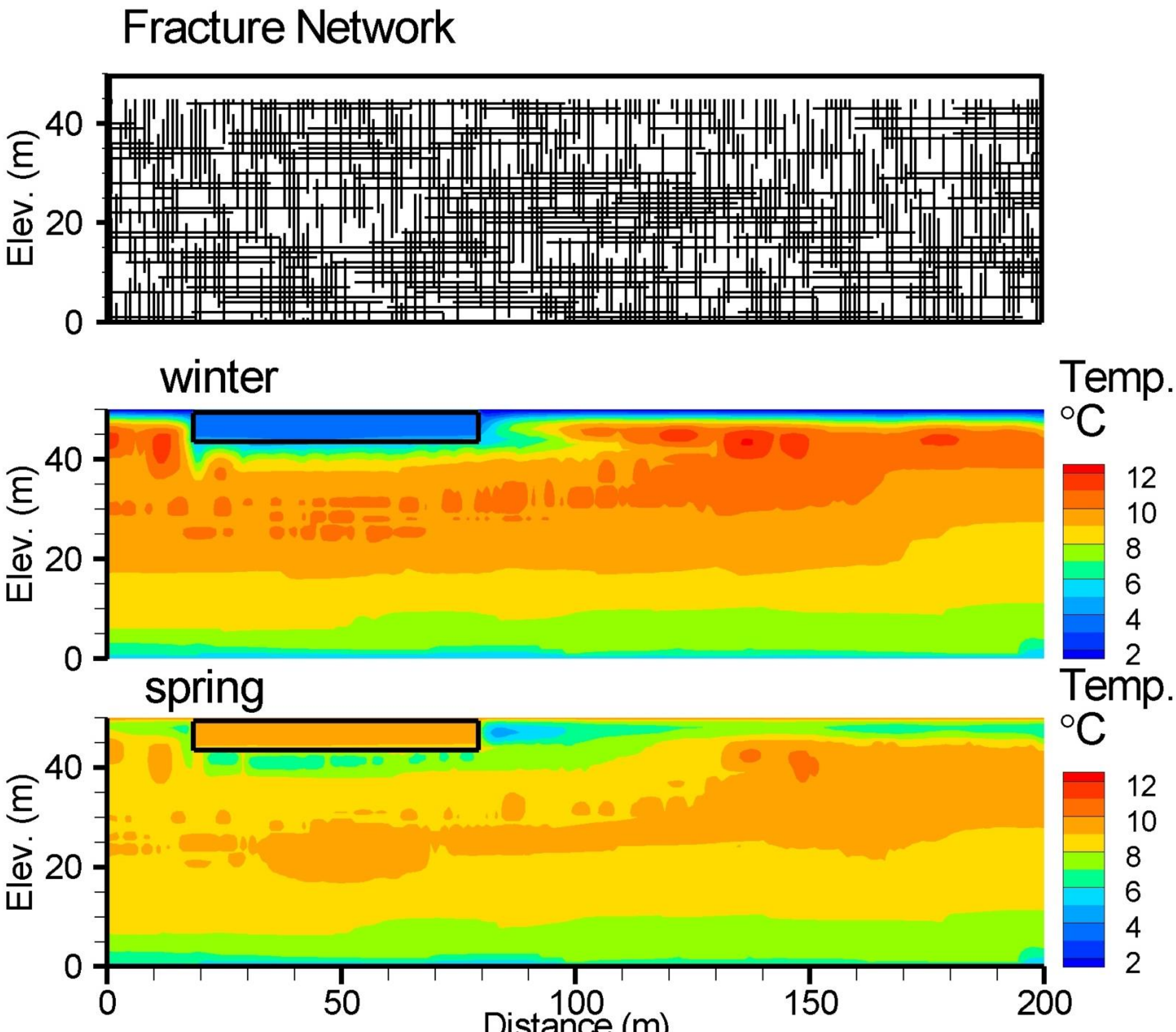
Case A:
Base T= +2 ˚C
Initial T= +1 ˚C
Ice T= -10 ˚C
Air T_{min}= -25, A= +29 ˚C

Black Smoker Simulation

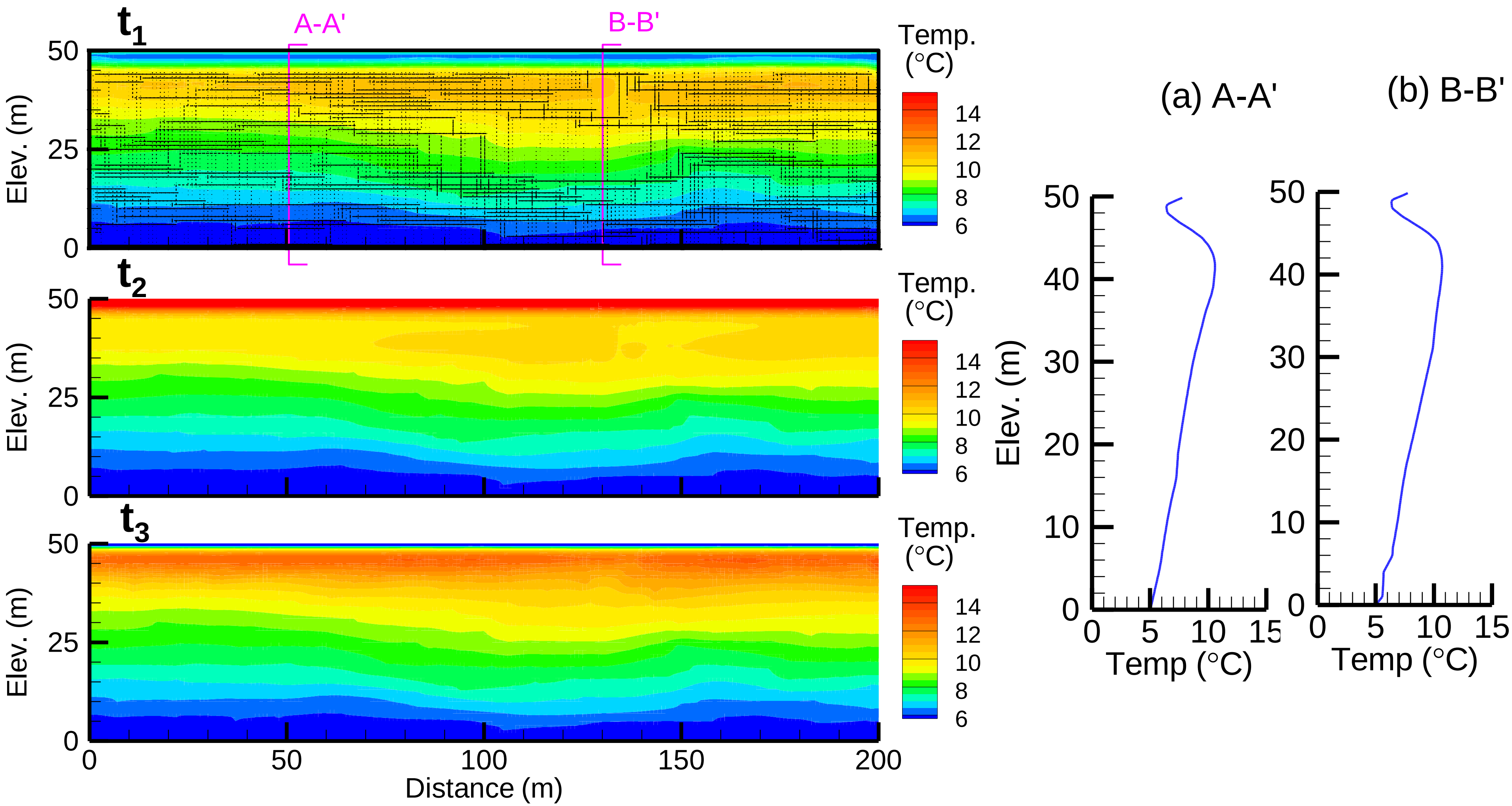
Smoker Heat Transport Model

(Yang et al. JGR, 1996)



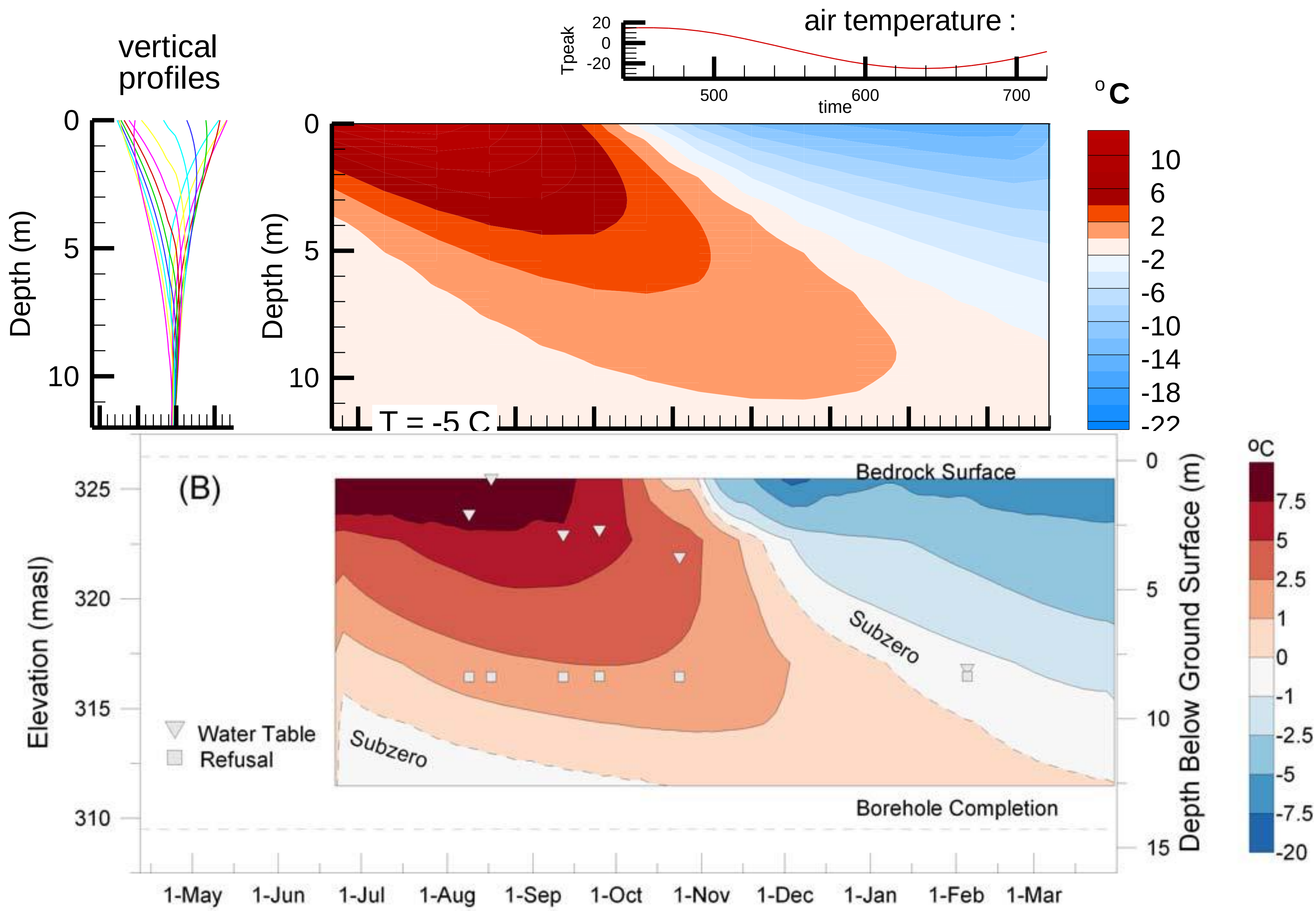

Fracture Network
Elev. (m)
0
20
40
winter
Temp. °C
12
10
8
6
4
2
spring
Distance (m)
0
50
100
150
200

Simulated Temperature Distributions ($\overline{2b}$=500μm)

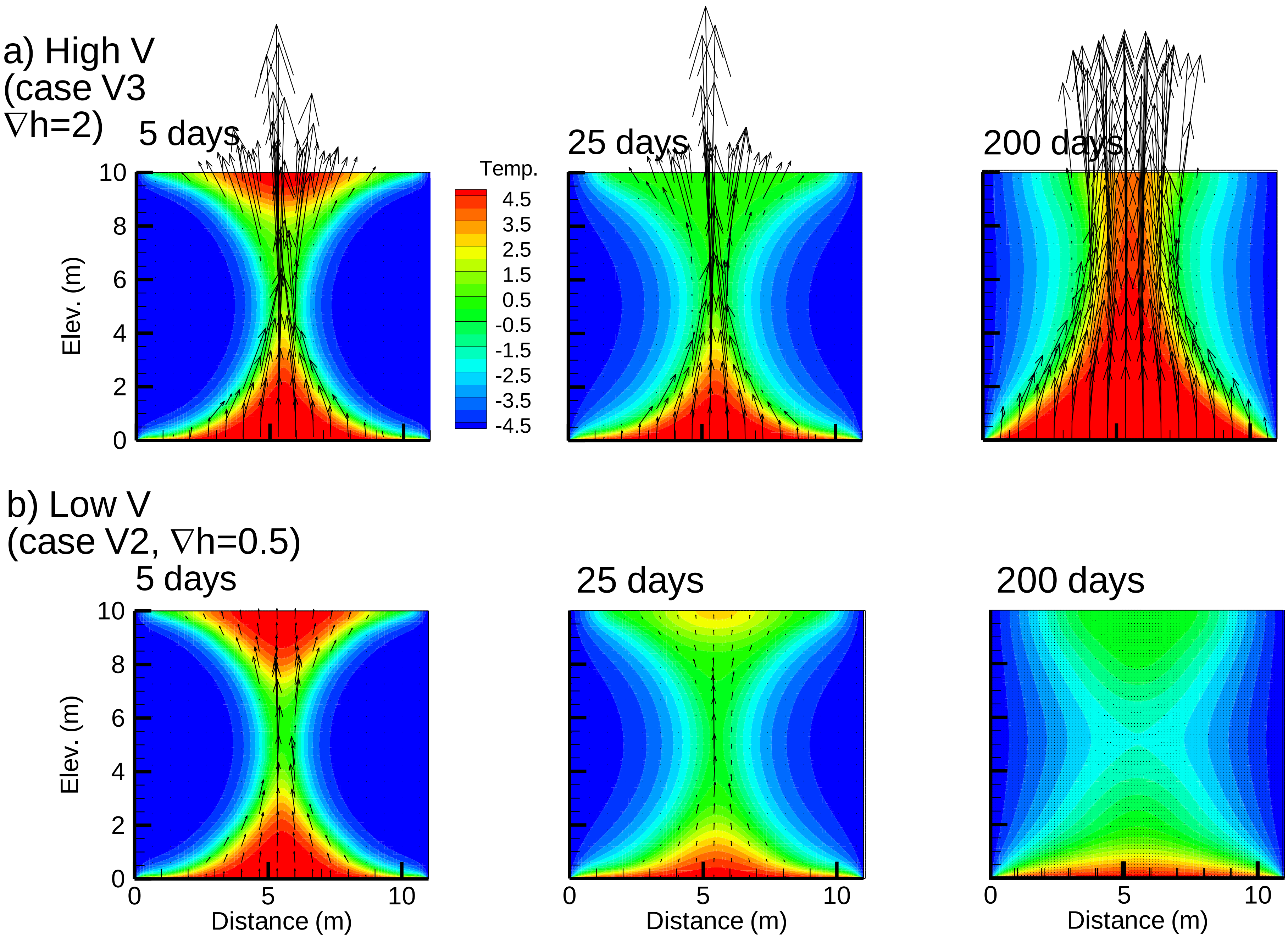


Simulated Subsurface Temperature Profiles

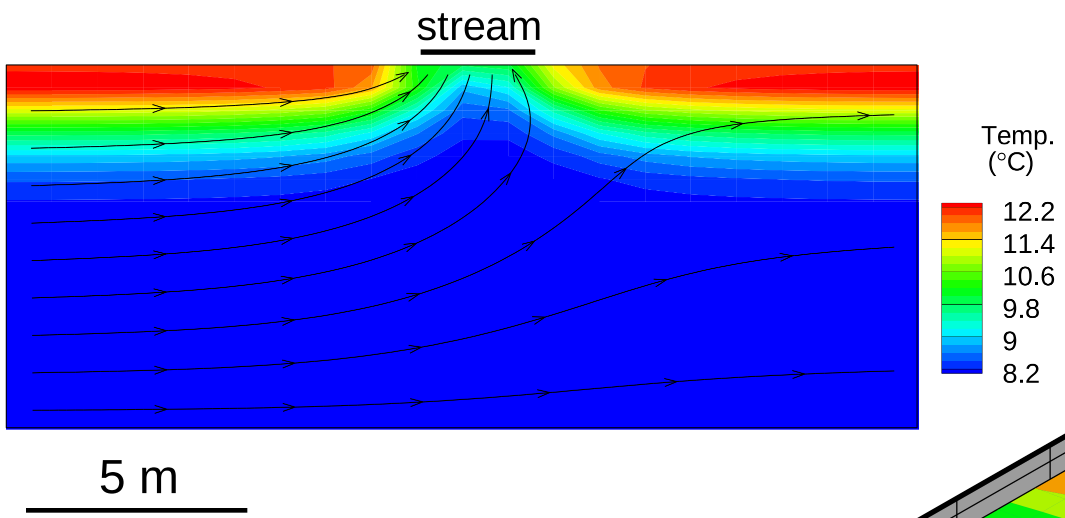
Heatflow model (Molson & Frind, 2009)

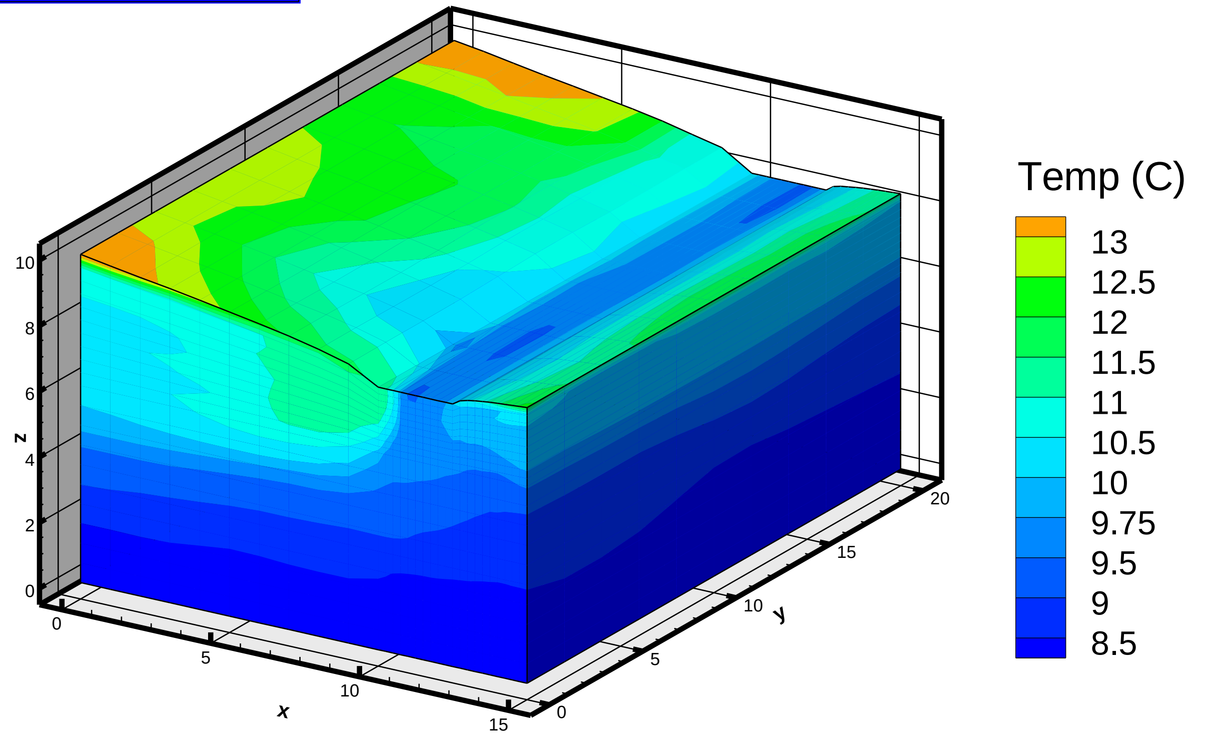


Benchmark TH3   SMOKER Model (Molson & Frind 2014)

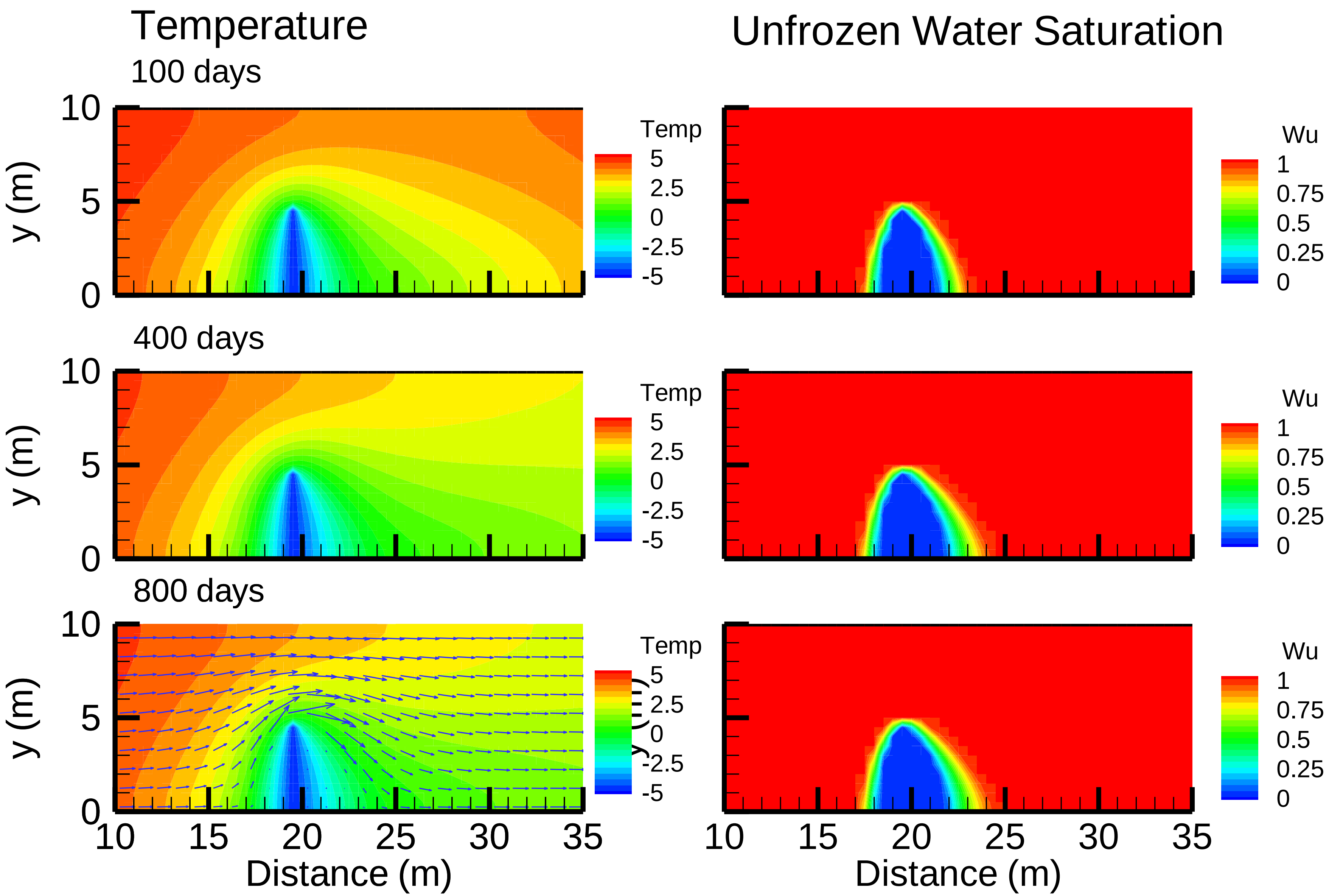


Groundwater – Surface Water Interaction:
Use of thermal regimes to quantify contaminant discharge

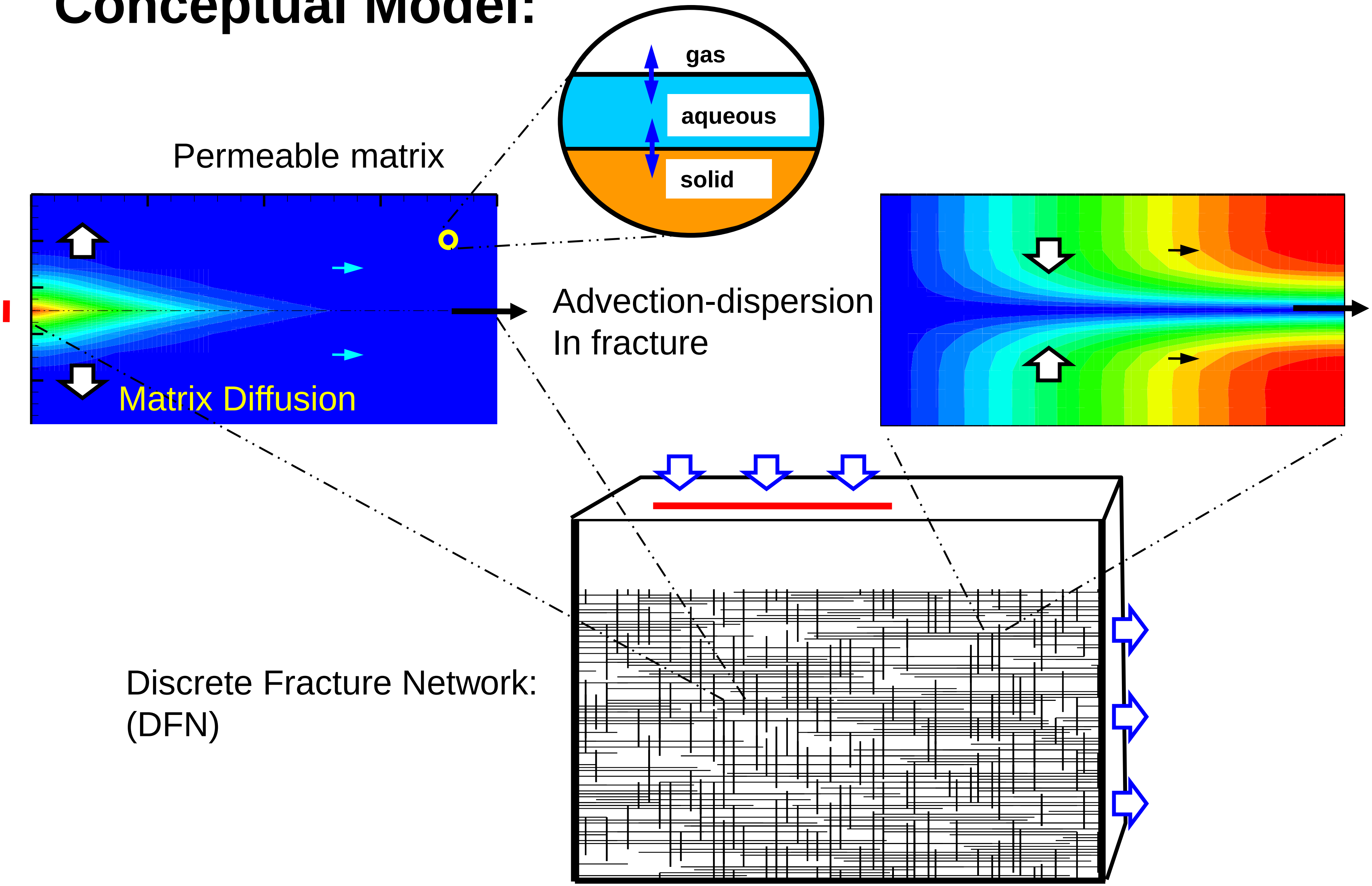




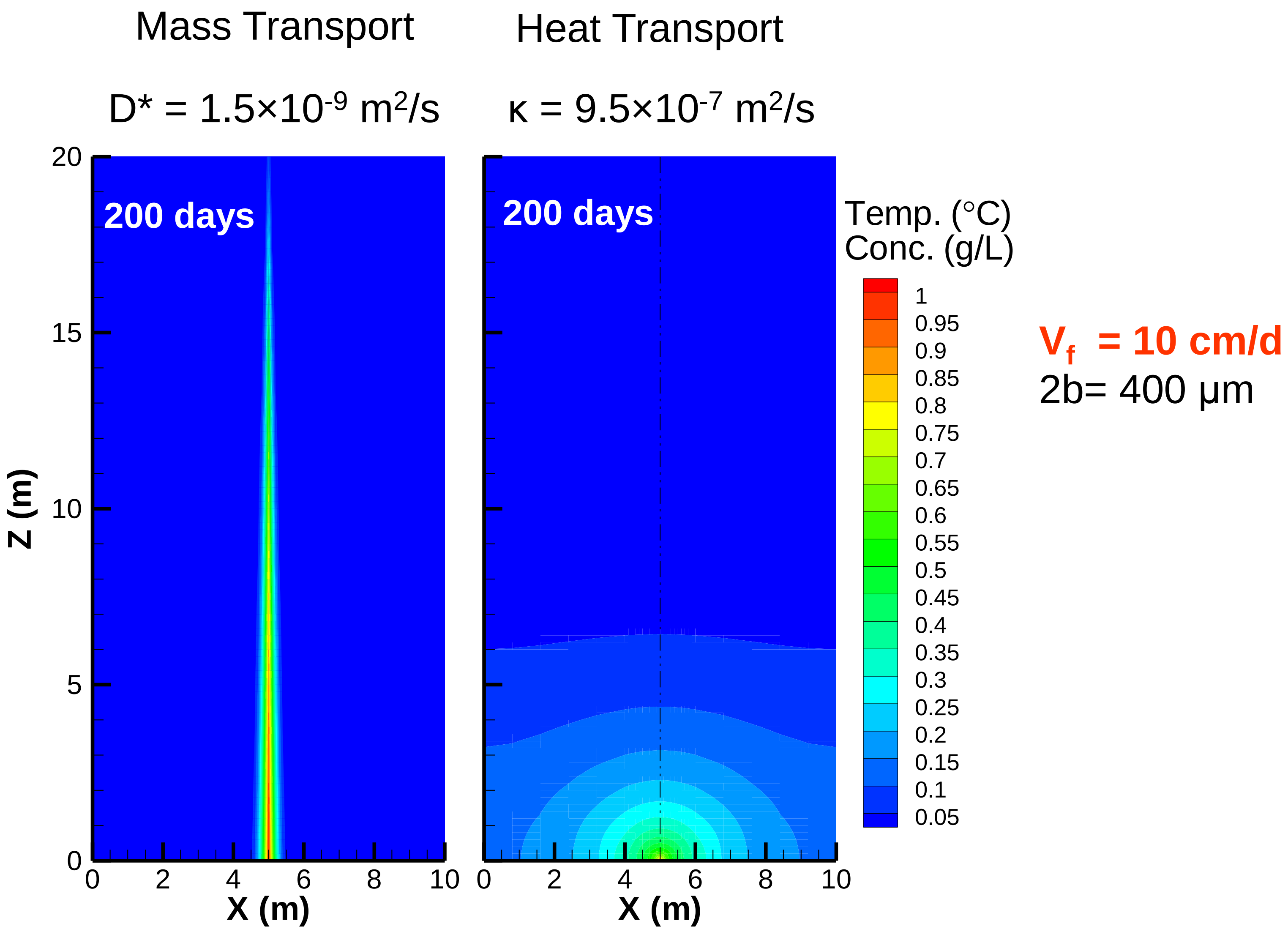
HEATFLOW Model: 3D Ice Wall Numerical Simulation

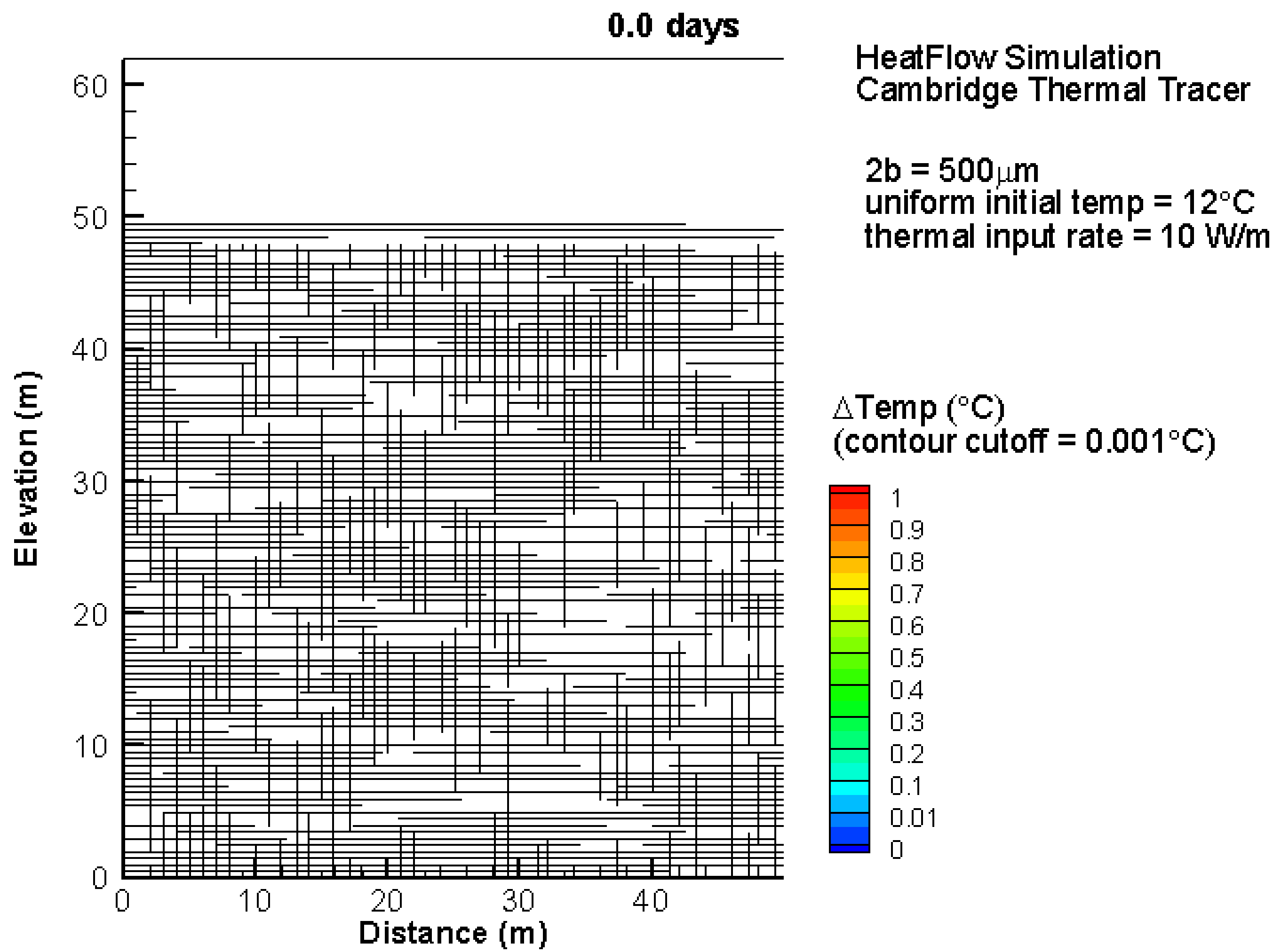


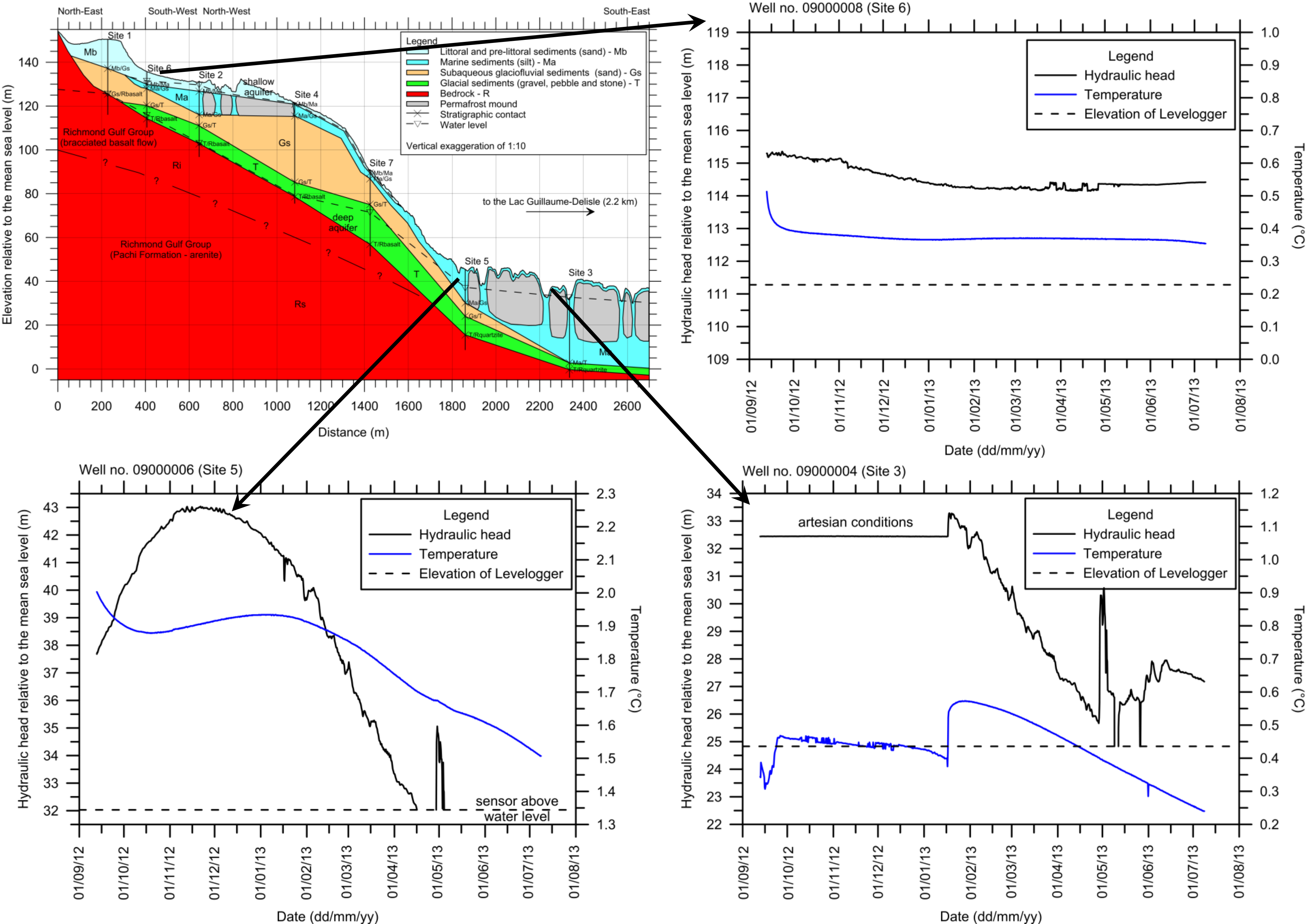
Conceptual Model:



Hydrodynamic Dispersion vs. Thermal Diffusivity

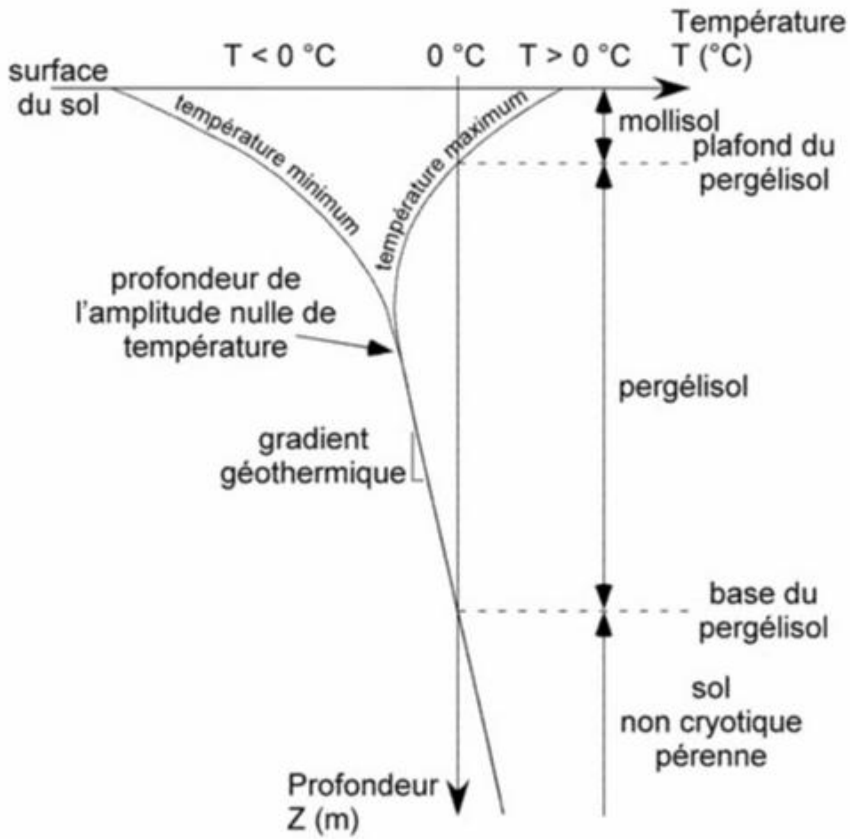



0.0 days
HeatFlow Simulation
Cambridge Thermal Tracer
2b = 500µm
uniform initial temp = 12°C
thermal input rate = 10 W/m
ΔTemp (°C)
(contour cutoff = 0.001°C)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.01
0
Elevation (m)
0
10
20
30
40
50
60
Distance (m)
0
10
20
30
40



North-East
South-West North-West
South-East
Site 1
Site 6
Site 2
Site 4
Site 7
Site 5
Site 3
shallow aquifer
deep aquifer
Mb
Ma
Gs
T
Ri
Rs
Richmond Gulf Group (bracciated basalt flow)
Richmond Gulf Group (Pachi Formation - arenite)
to the Lac Guillaume-Delisle (2.2 km)
Legend
Littoral and pre-littoral sediments (sand) - Mb
Marine sediments (silt) - Ma
Subaqueous glaciofluvial sediments (sand) - Gs
Glacial sediments (gravel, pebble and stone) - T
Bedrock - R
Permafrost mound
Stratigraphic contact
Water level
Vertical exaggeration of 1:10
Elevation relative to the mean sea level (m)
Distance (m)
Well no. 09000008 (Site 6)
Well no. 09000006 (Site 5)
Well no. 09000004 (Site 3)
Hydraulic head
Temperature
Elevation of Levelogger
Hydraulic head relative to the mean sea level (m)
Temperature (°C)
Date (dd/mm/yy)
artesian conditions
sensor above water level

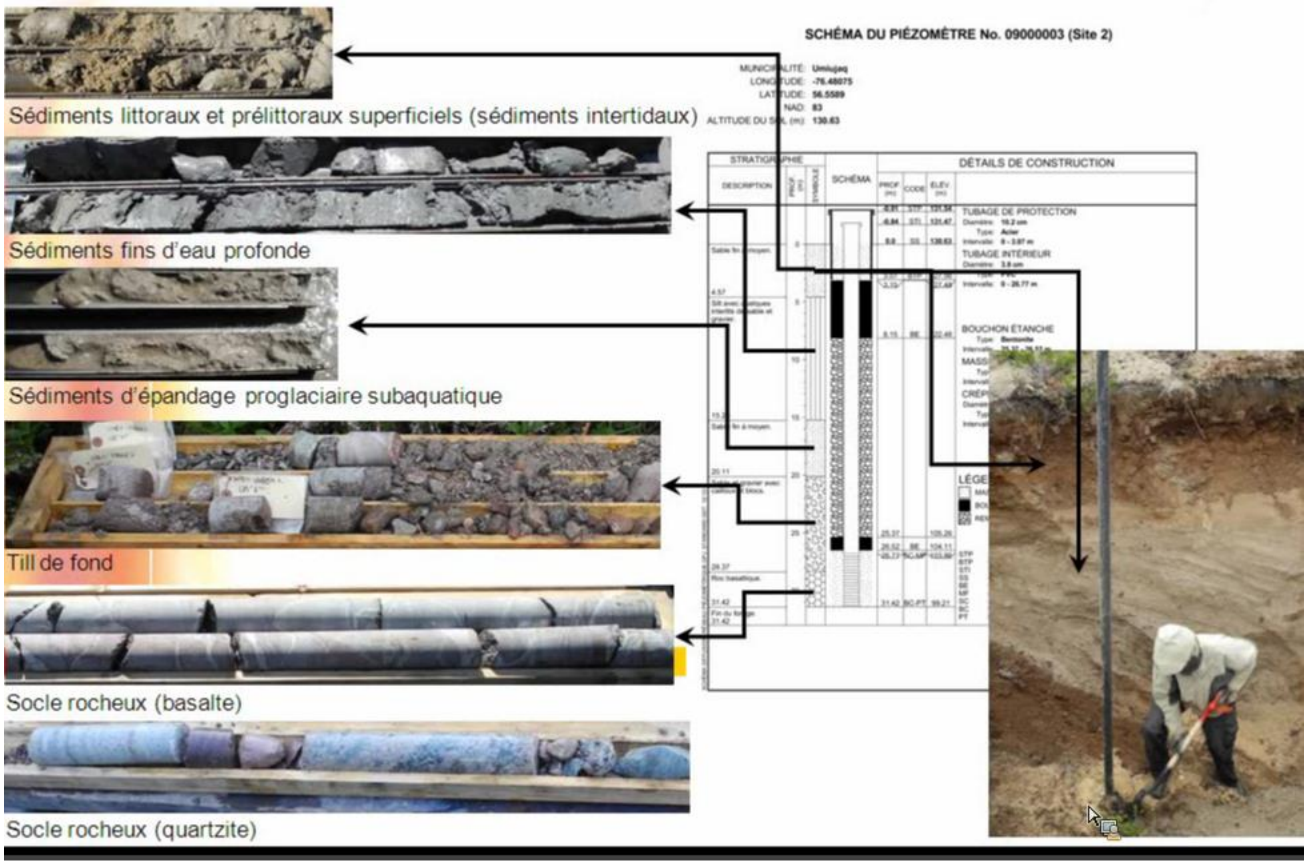
Le pergélisol: quelques concepts
(profil thermique , définitions du pergélisol et du mollisol)



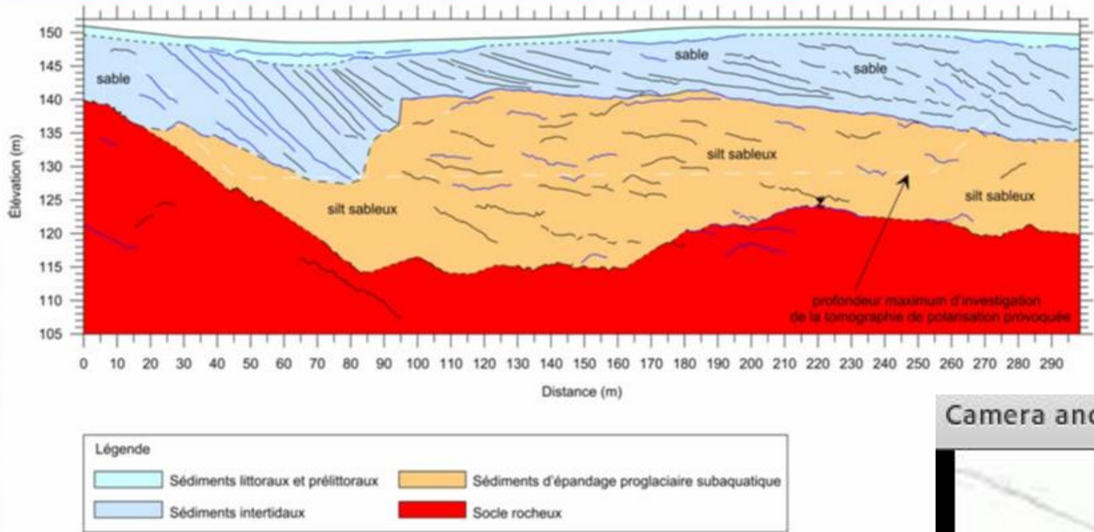
Mollisol:
couche superficielle
affectée par les cycles
de gel-dégel.

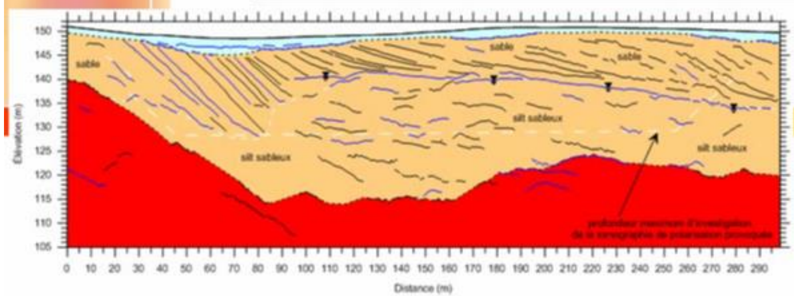
Pergélisol:
sol ou roche dont la
température demeure
sous 0 °C durant au
moins deux années.

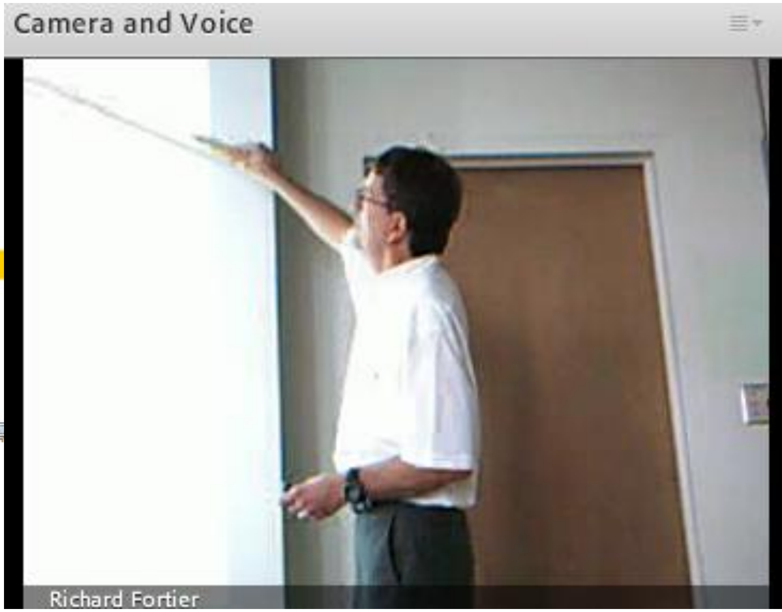
Deuxième exemple d'un bassin versant à Umiujaq
(investigation hydrogéologique: campagne de forages à l'été 2012)



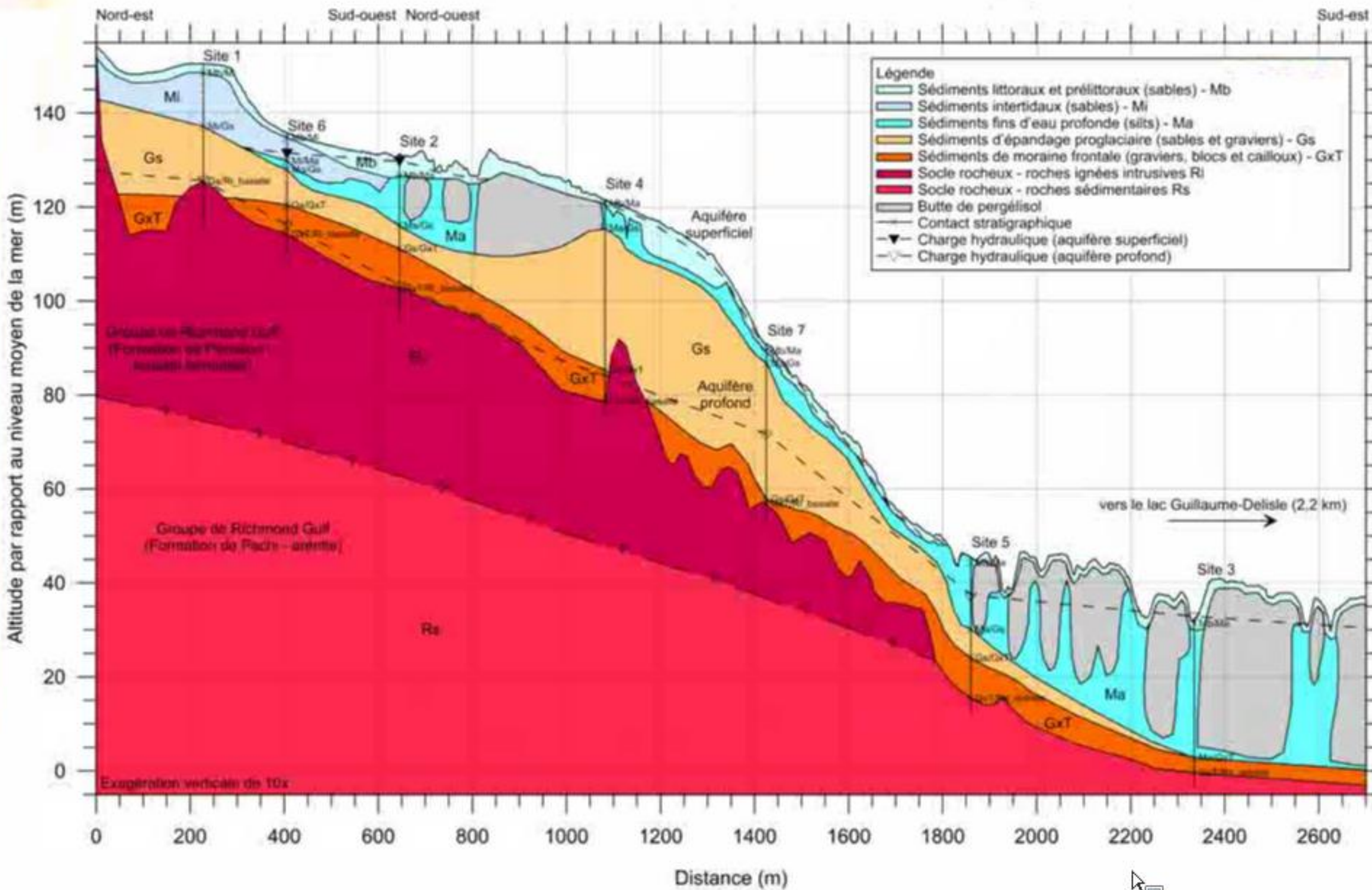
Deuxième exemple d'un bassin versant à Umiujaq
(investigation cryohydrogéophysique: coupe hydrostratigraphique interprétative)







Deuxième exemple d'un bassin versant à Umiujaq
(investigation hydrogéologique: coupe cryohydrostratigraphique interprétative)



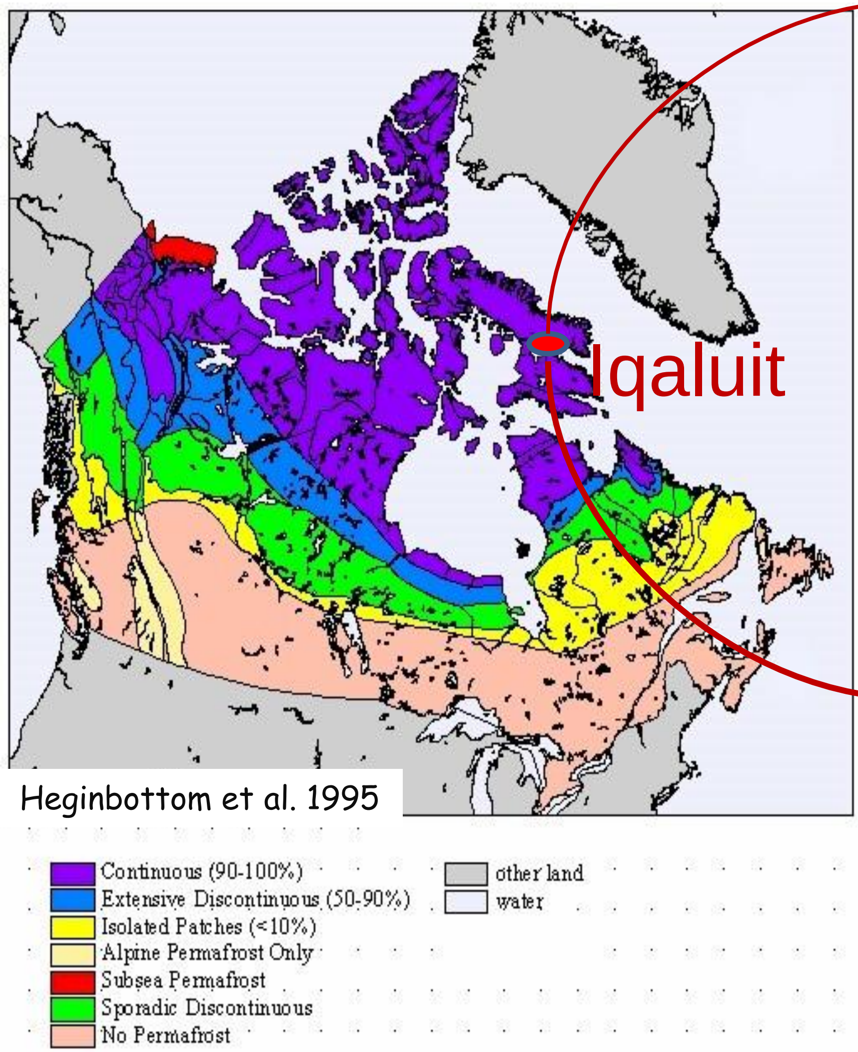
Numerical simulation of coupled groundwater flow and heat transport in a continuous permafrost environment : Iqaluit, Canada

Masoumeh Shojae Ghias, René Therrien, John Molson, Jean-Michel Lemieux

Université Laval, Quebec City, Canada

Study site: Iqaluit airport

Permafrost map of Canada



Heginbottom et al. 1995

Iqaluit airport

- Latitude of 63°45′ N
- Continuous permafrost
- Mean Annual T: -7.76 C

Current Issues at Iqaluit airport

Thaw settlement

Ice wedges

Frost cracks

Depressions

Resurfacing

Concrete patch

Site investigation at Iqaluit airport

Surface and subsurface geology

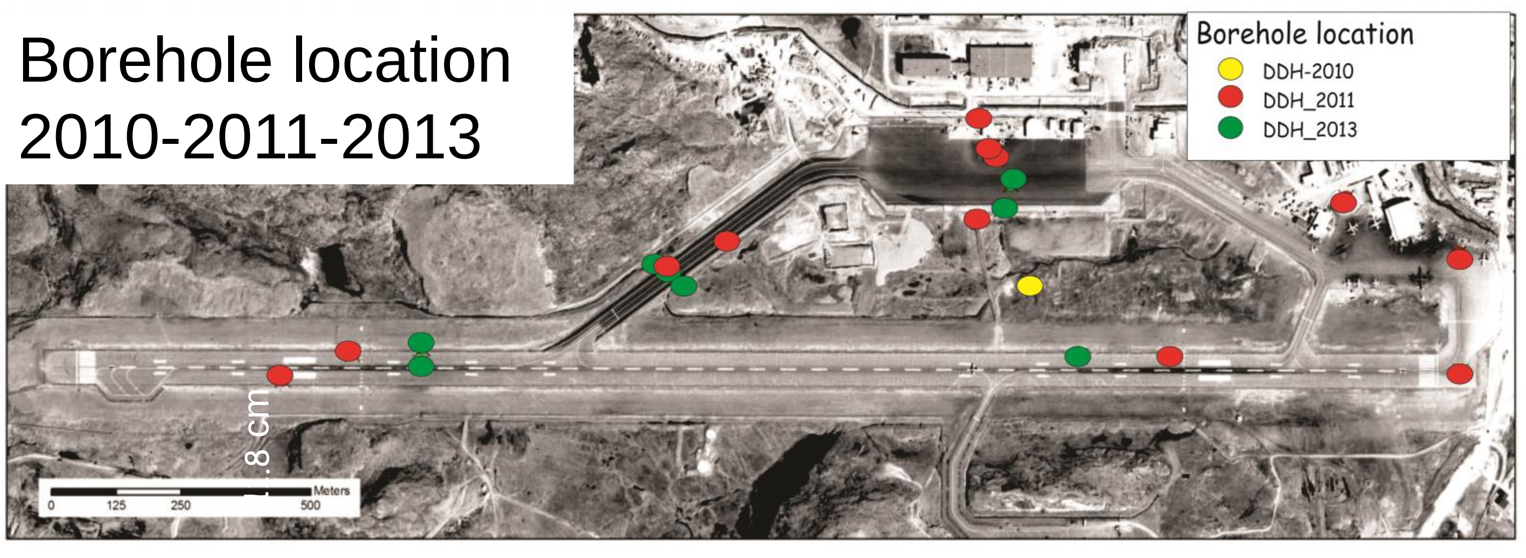
- Drilling, coring
- Geophysical survey
- Lab analysis

Climate related data

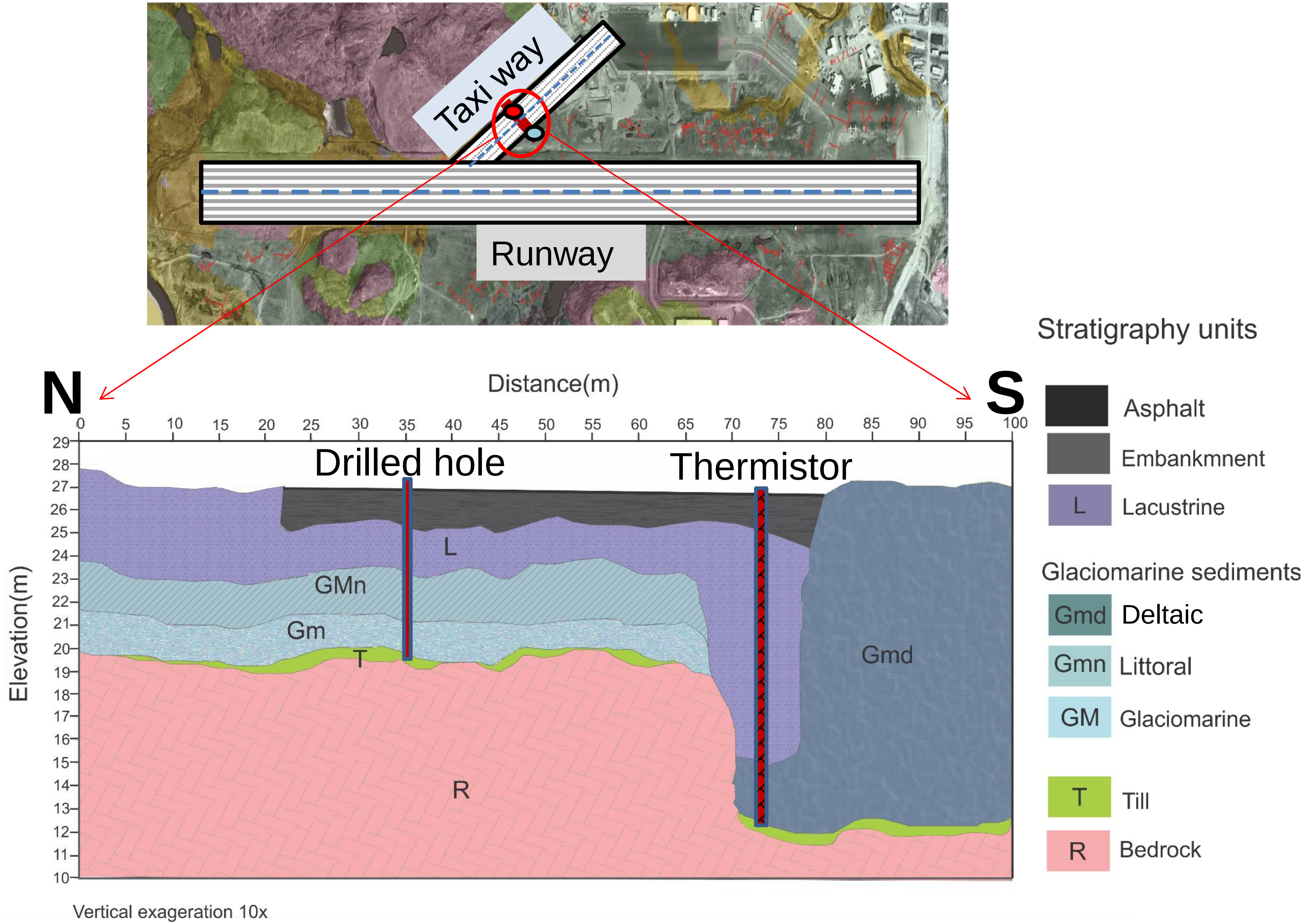
- Surface and subsurface T
- Snow depth

Ground movement

Borehole location
2010-2011-2013

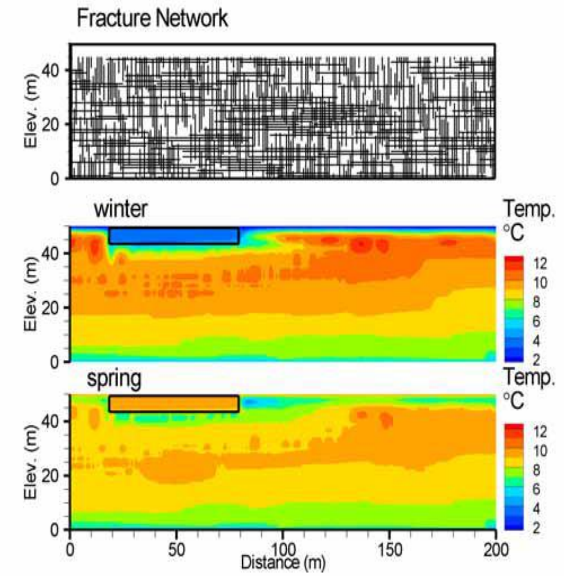


Conceptual Geological Cross-section



HEATFLOW-SMOKER MODEL(Molson et al. 2012)

- 3D finite element
- Freezing and thawing and latent heat
- Partially saturated zone for thermal transport

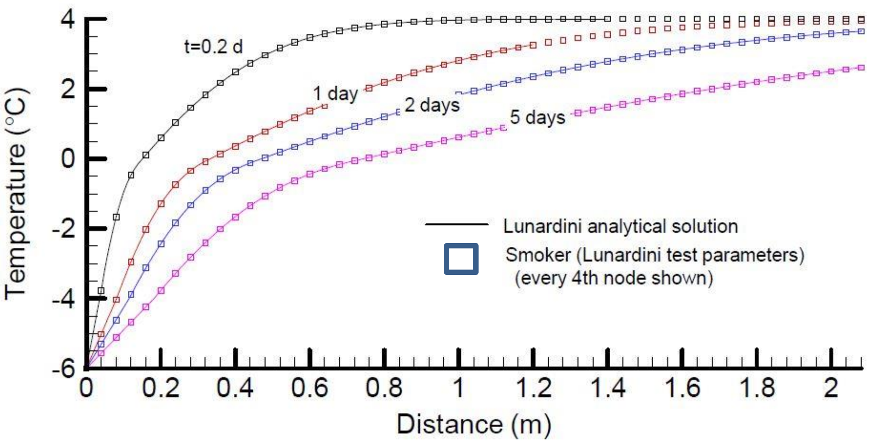


- Coupled density dependent flow and thermal transport

Validation of HEATFLOW-SMOKER

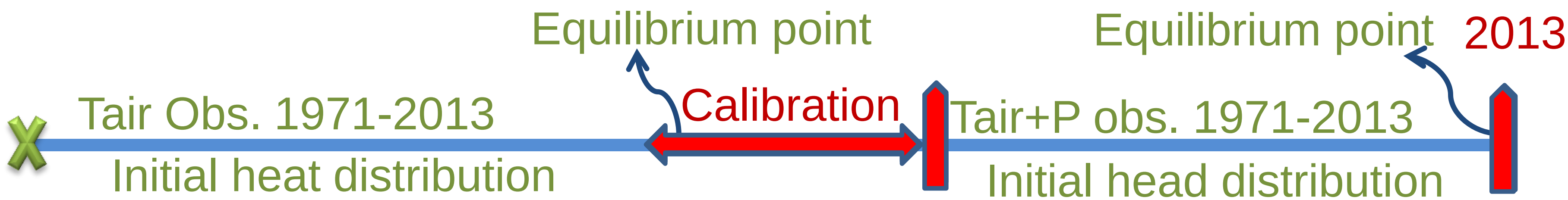
- Numerical vs. analytical model

(Lunardini, 3-zone freezing-front problem)



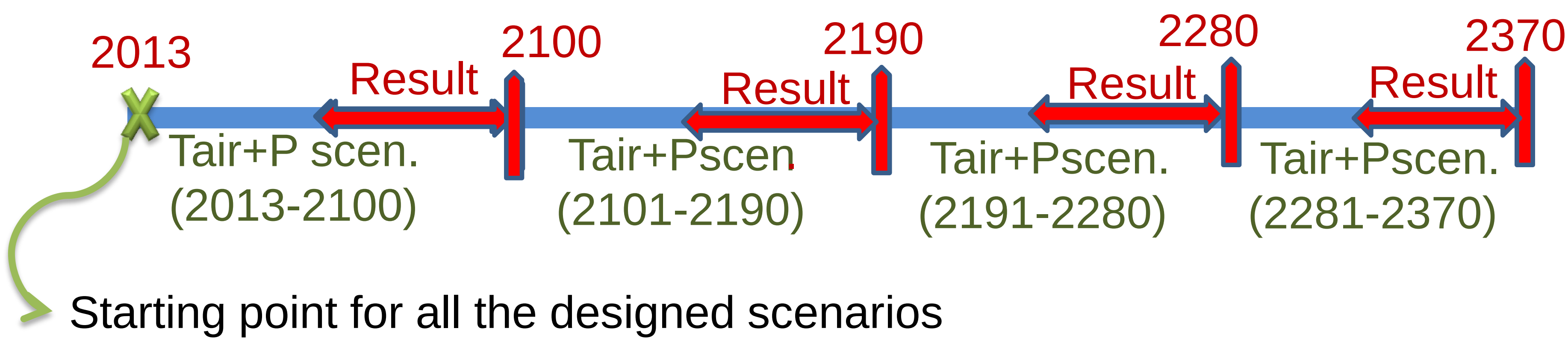
Coupled heat-fluid flow model

1. Calibration

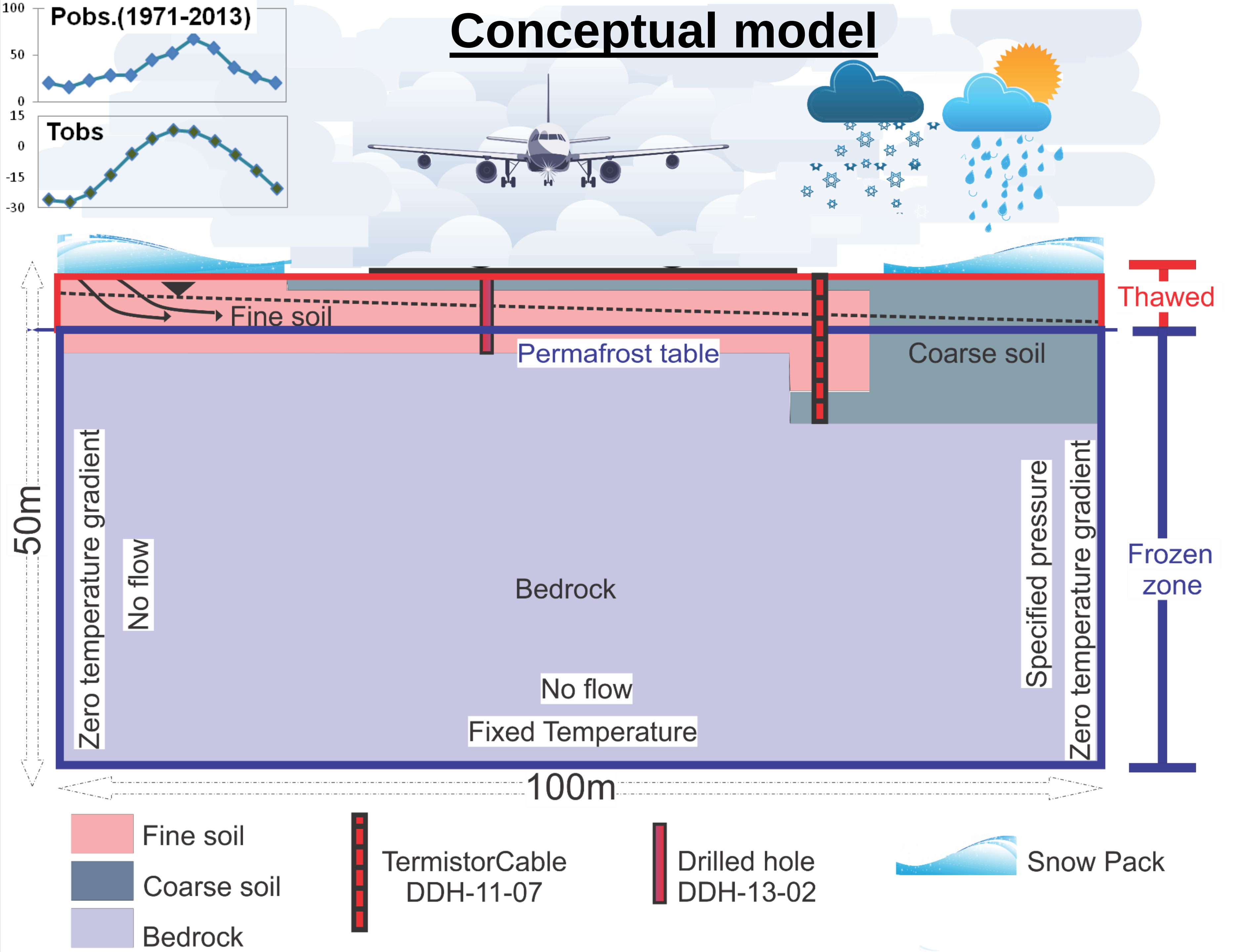


2. Designed scenarios

SR-1. Saturated vs. unsaturated
SR-2. Advection-conduction vs. conduction heat transport
SR-3. Heterogeneous hydraulic conductivity distribution

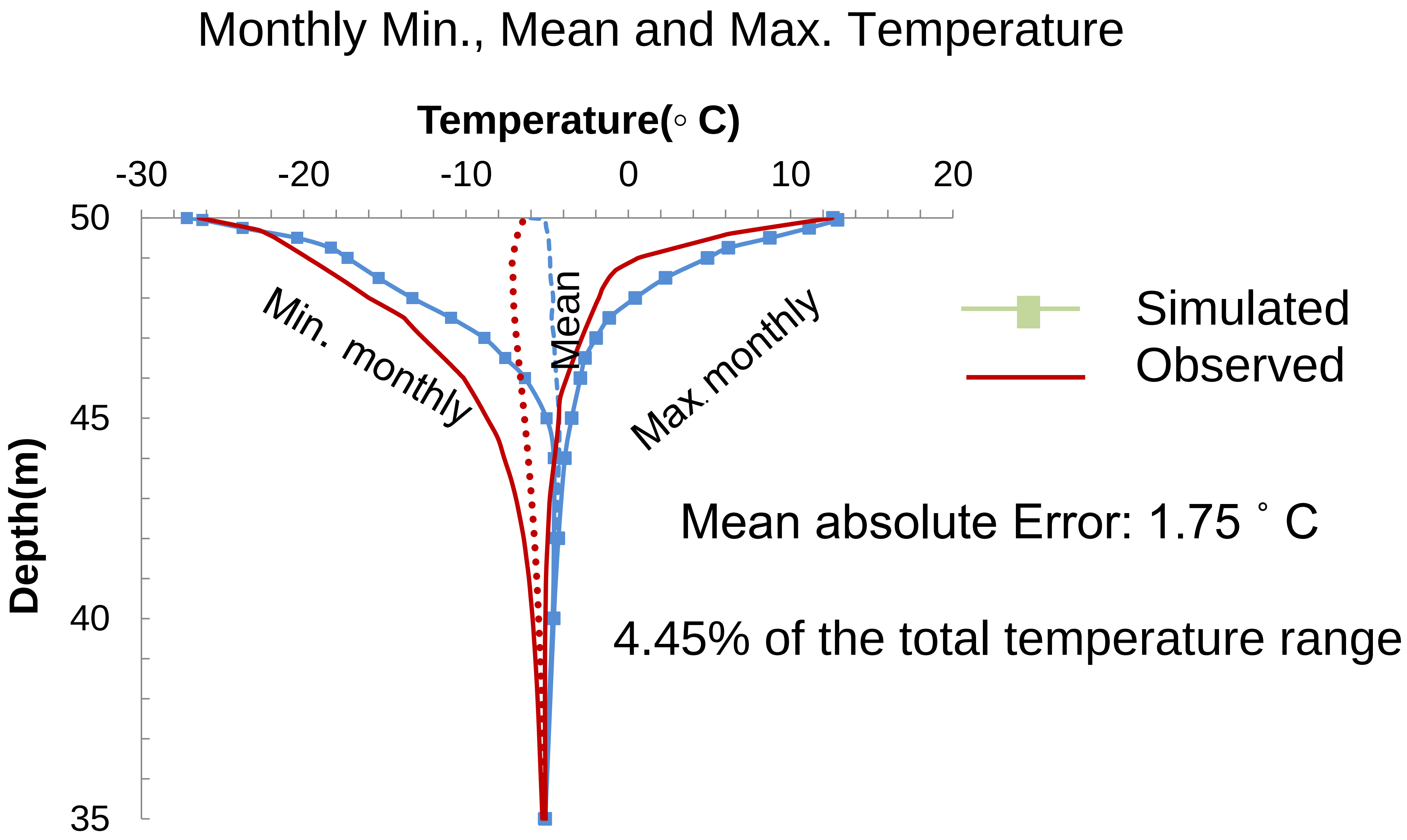


Conceptual model

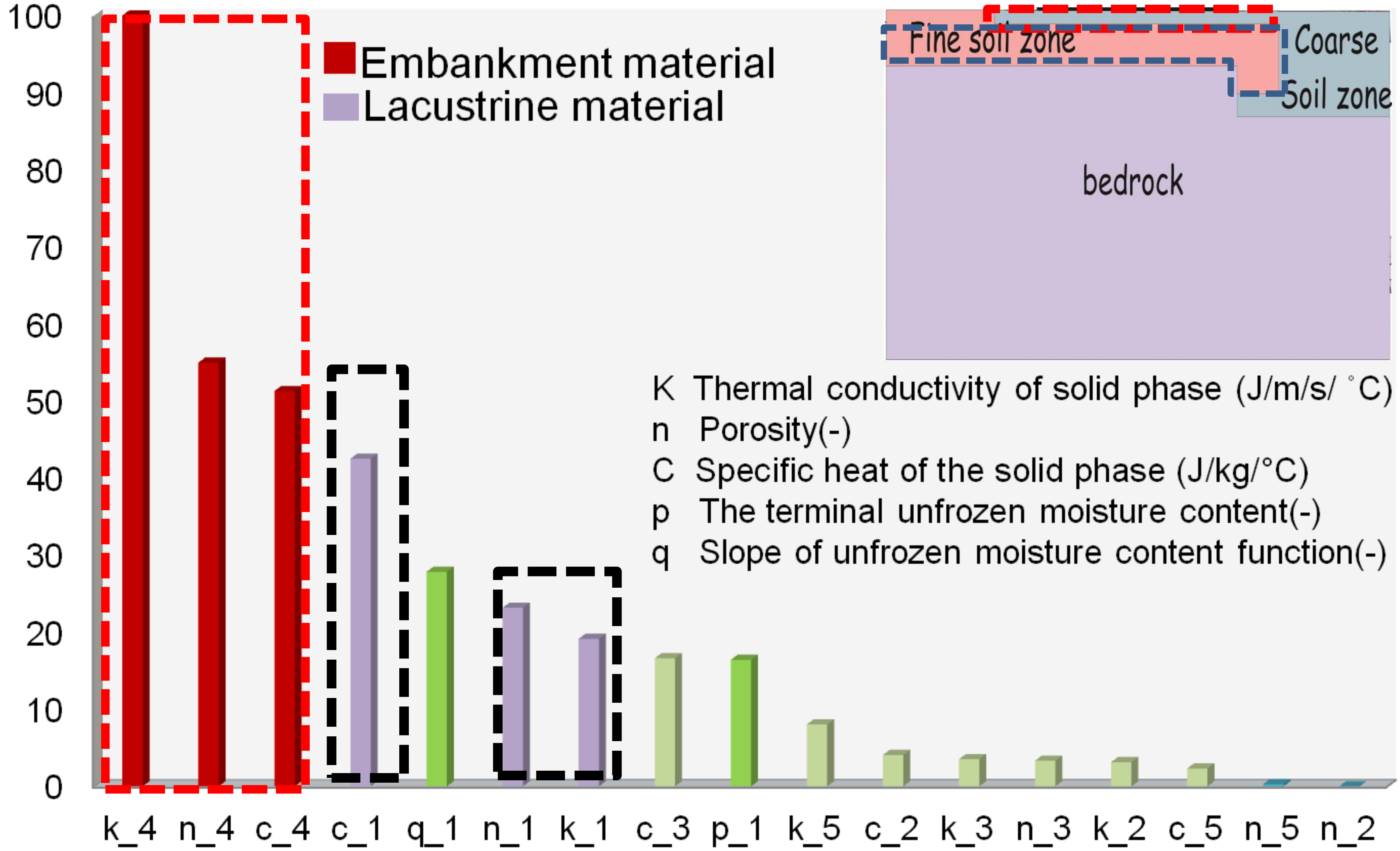


Model calibration

Temperature for the last year of simulation for 1971-2012



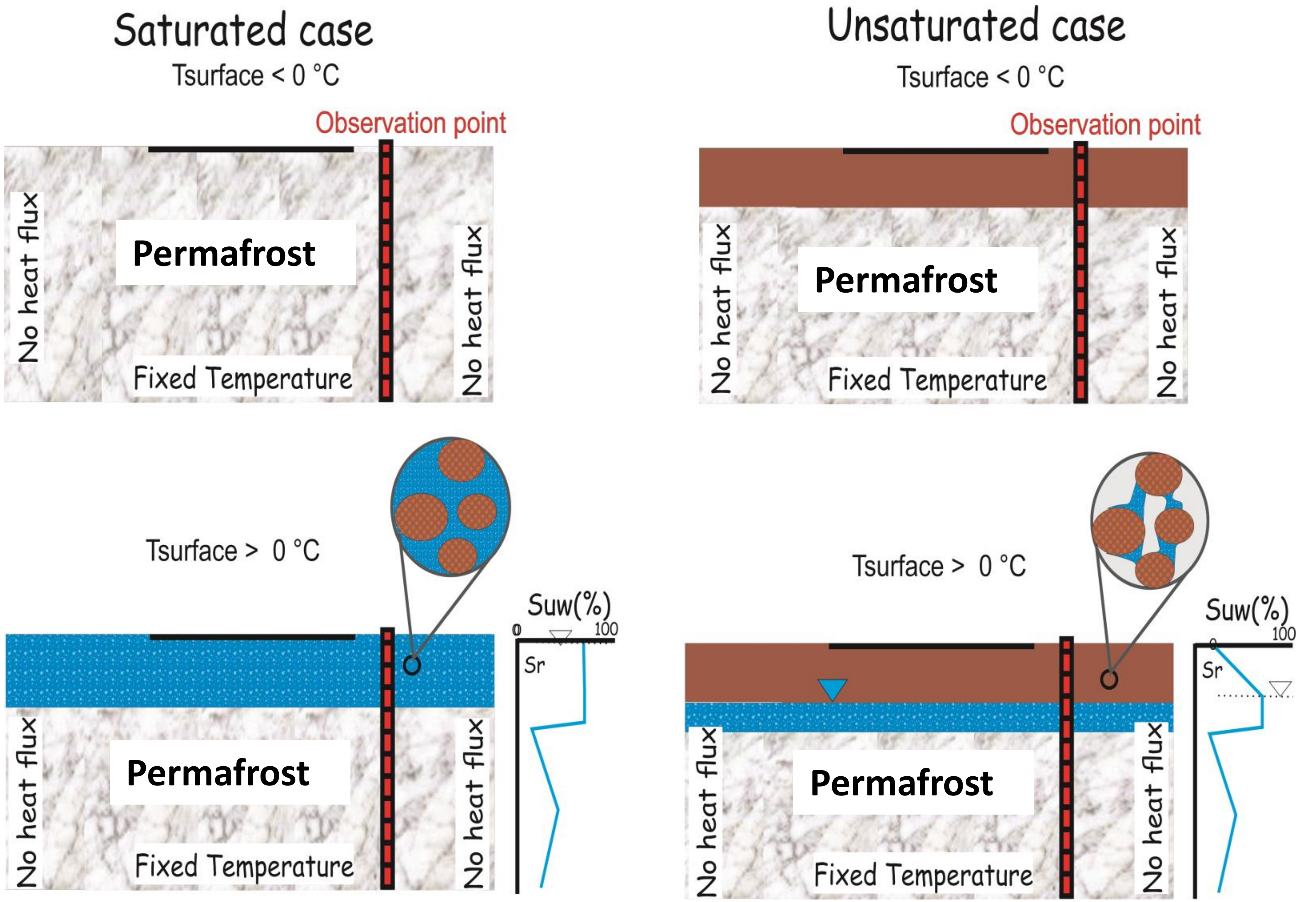
Sensitivity Analysis



Future climate warming scenarios

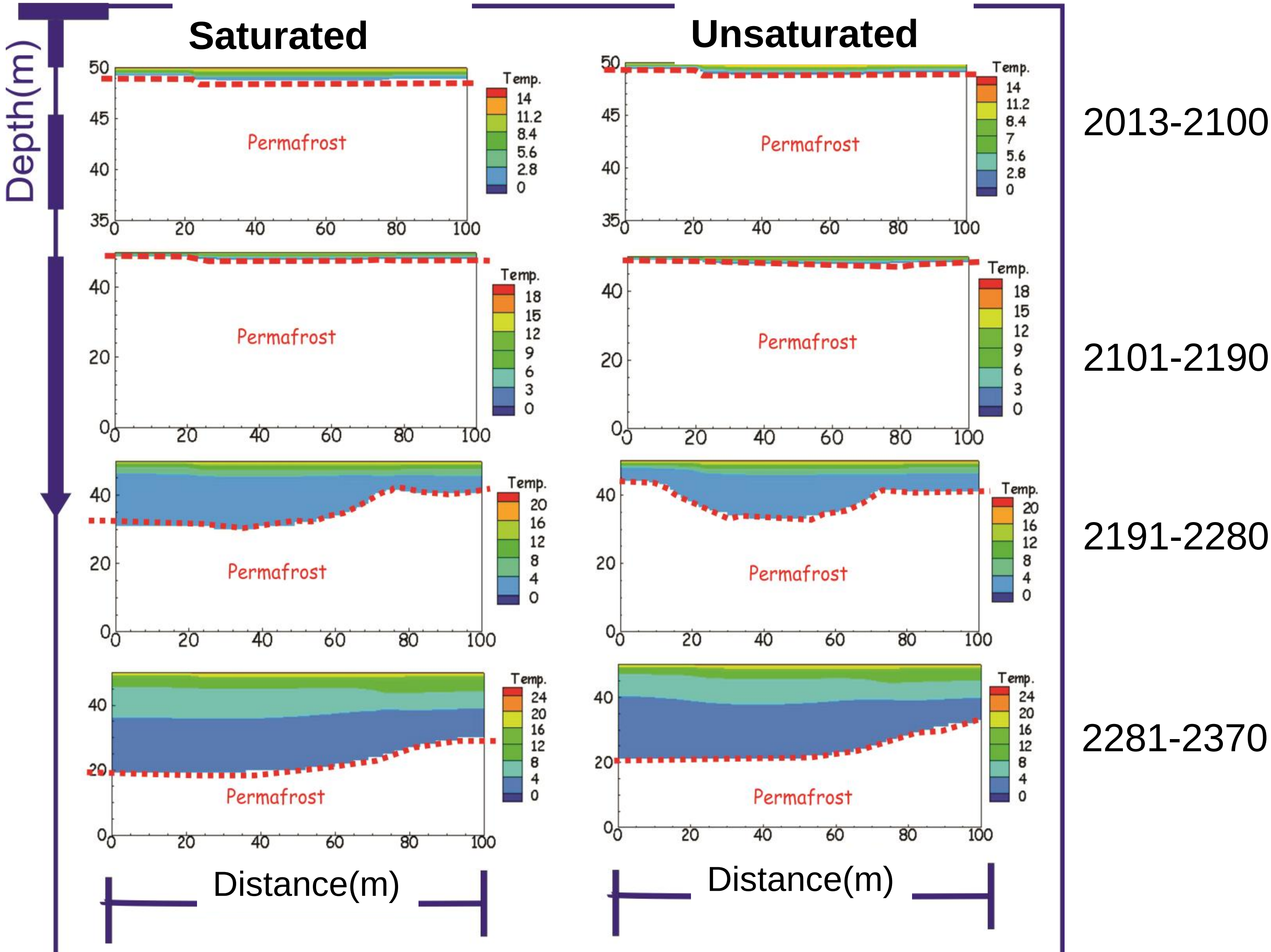
- Data from GCM (AR4, IPCC 2007)
- SR-B1, SR-A1B, SR-A2 (low, medium and high greenhouse gas emission scenario)
- Time period: 2071–2100
- Downscale method : Delta change

Sr-1: effects of saturated vs unsaturated on permafrost

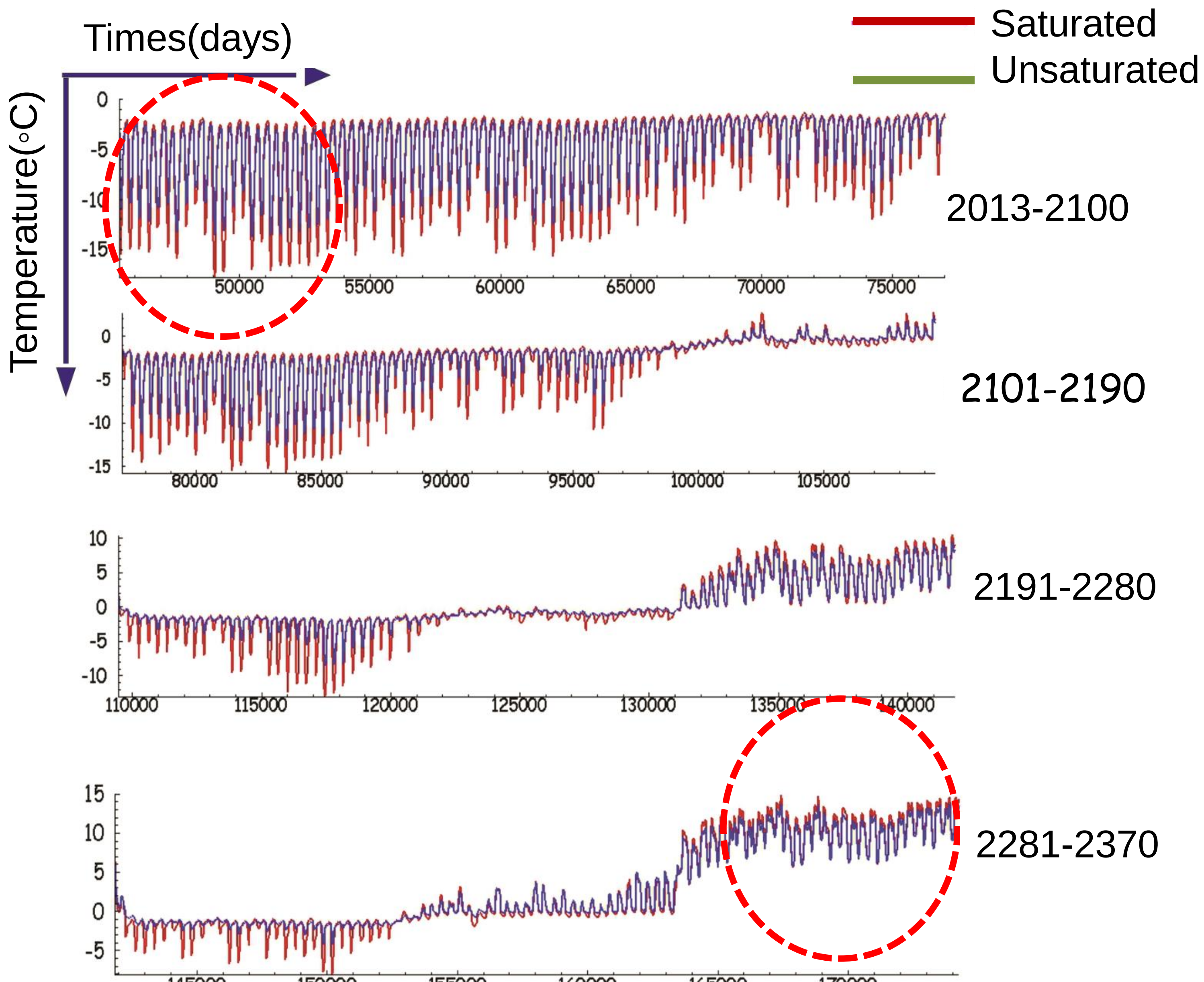


SR-1: Comparison of completely saturated and partly unsaturated model on permafrost thaw under future climate warming

Result Plotted for the last September of each warming period



SR- 1. Temperature changes as a function of time at a 2.5 m depth



Conclusion

- ✓ Calibration of simplified 2D model
  - ✓ Best for Winter months
  - ✓ Greater difference for spring and early summer

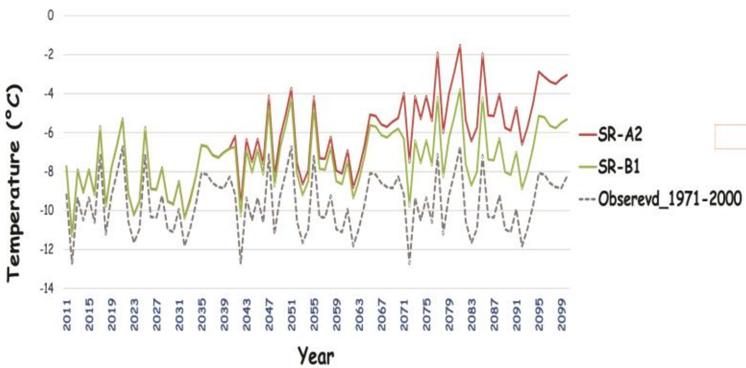
- ✓ Key parameter : thermal conductivity of the uppermost soil layer

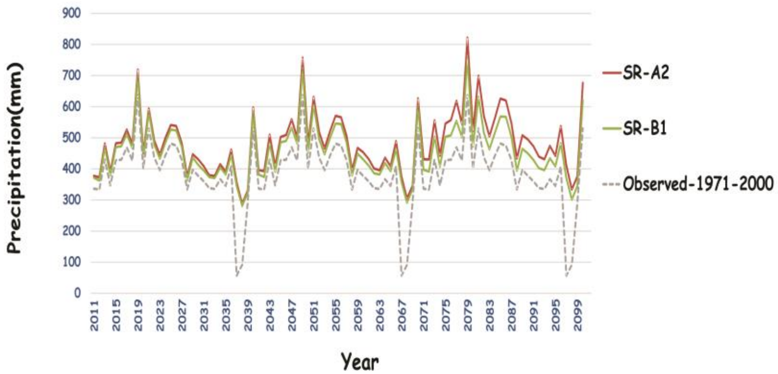
- ✓ **Saturated** vs. unsaturated upper zone
  - ✓ Differences are greater for negative temperatures at surface
  - ✓ Active layer expands faster under the same climate warming
  - ✓ Deeper permafrost table

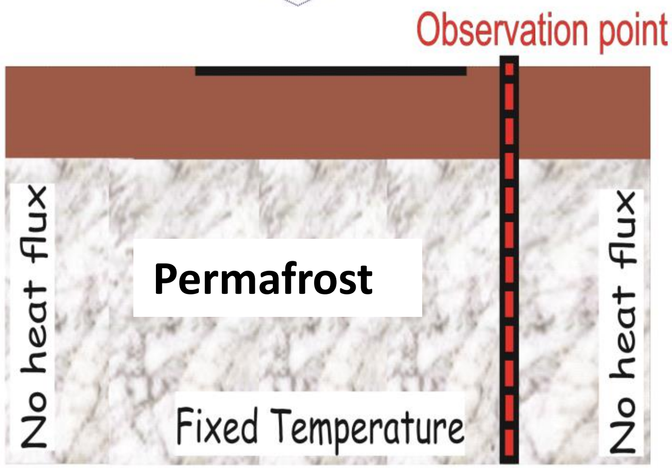
Ongoing work
SR- 2. Conductive vs advective conductive model

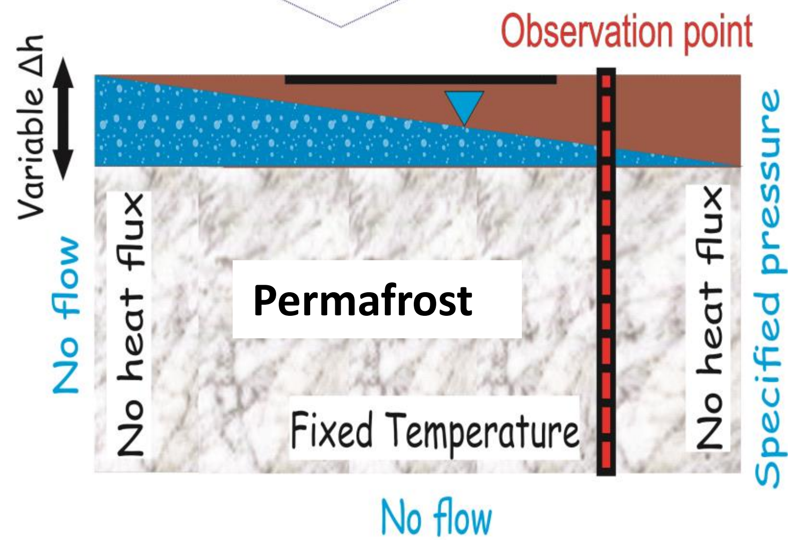
Conduction model

Conduction-advection model





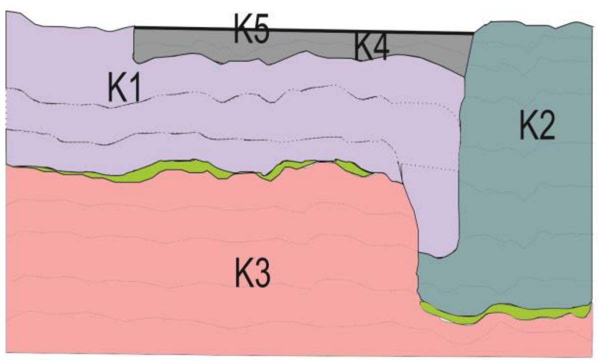




Ongoing work

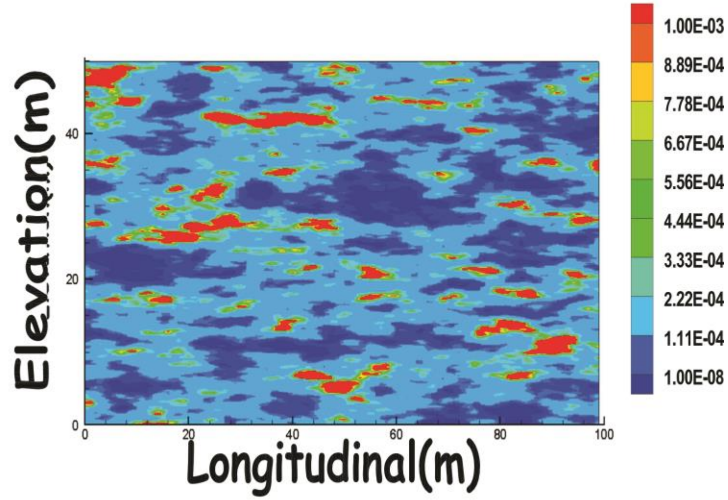
<u>SR-3. Effects of heterogeneous hydraulic conductivity on permafrost</u>

Natural layer



$K = 10^{-12} - 10^{-3}$ (m/sec)

Random K field



$10^{-8} < K < 10^{-3}$ (m/sec)

Acknowledgement

Natural Resources Canada / Ressources naturelles Canada

Canada

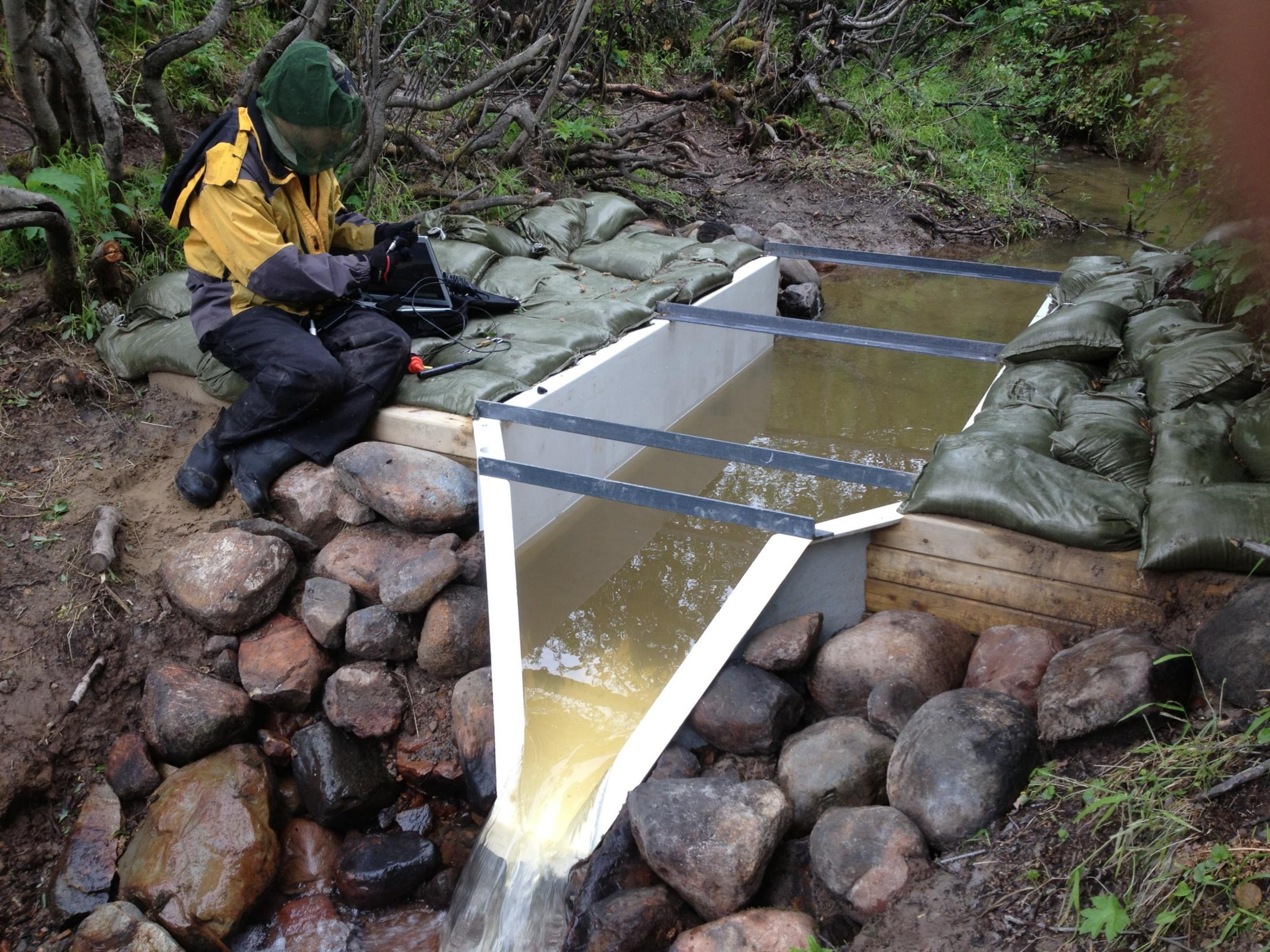
Natural Sciences and Engineering Research Council of Canada / Conseil de recherches en sciences naturelles et en génie du Canada

Canada

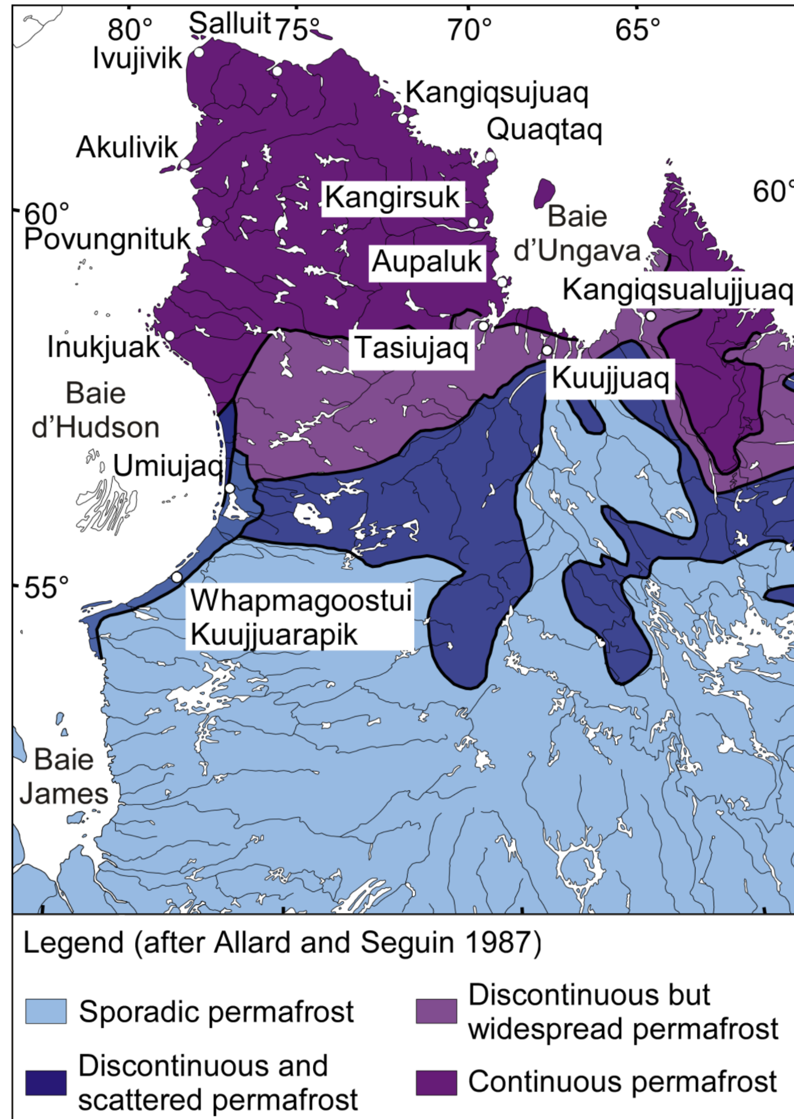
CENTRE D'ÉTUDES NORDIQUES

CEN Centre for Northern Studies

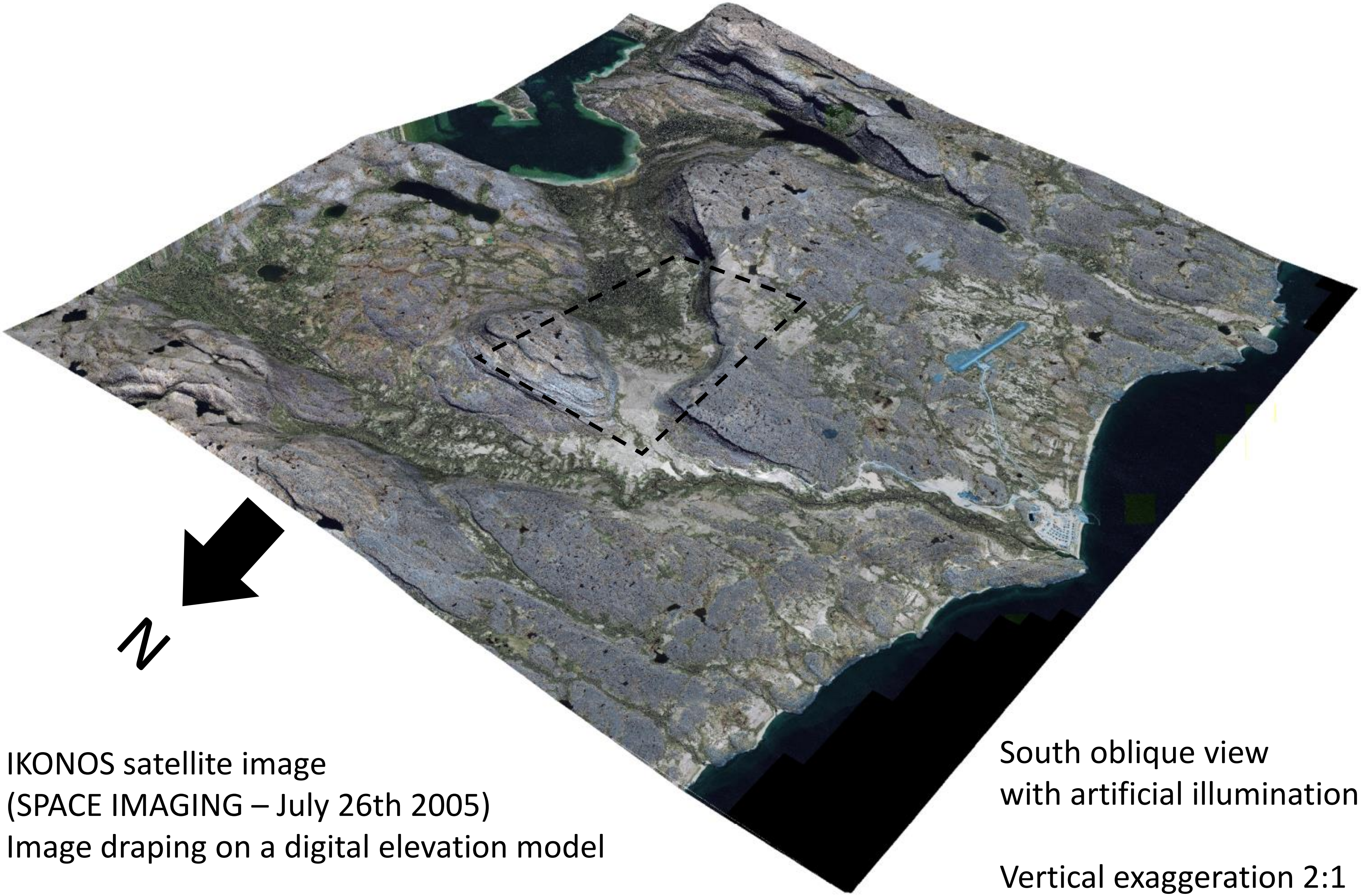

HERON
WATER TAPE



Permafrost in Northern Québec



Immatsiak network location

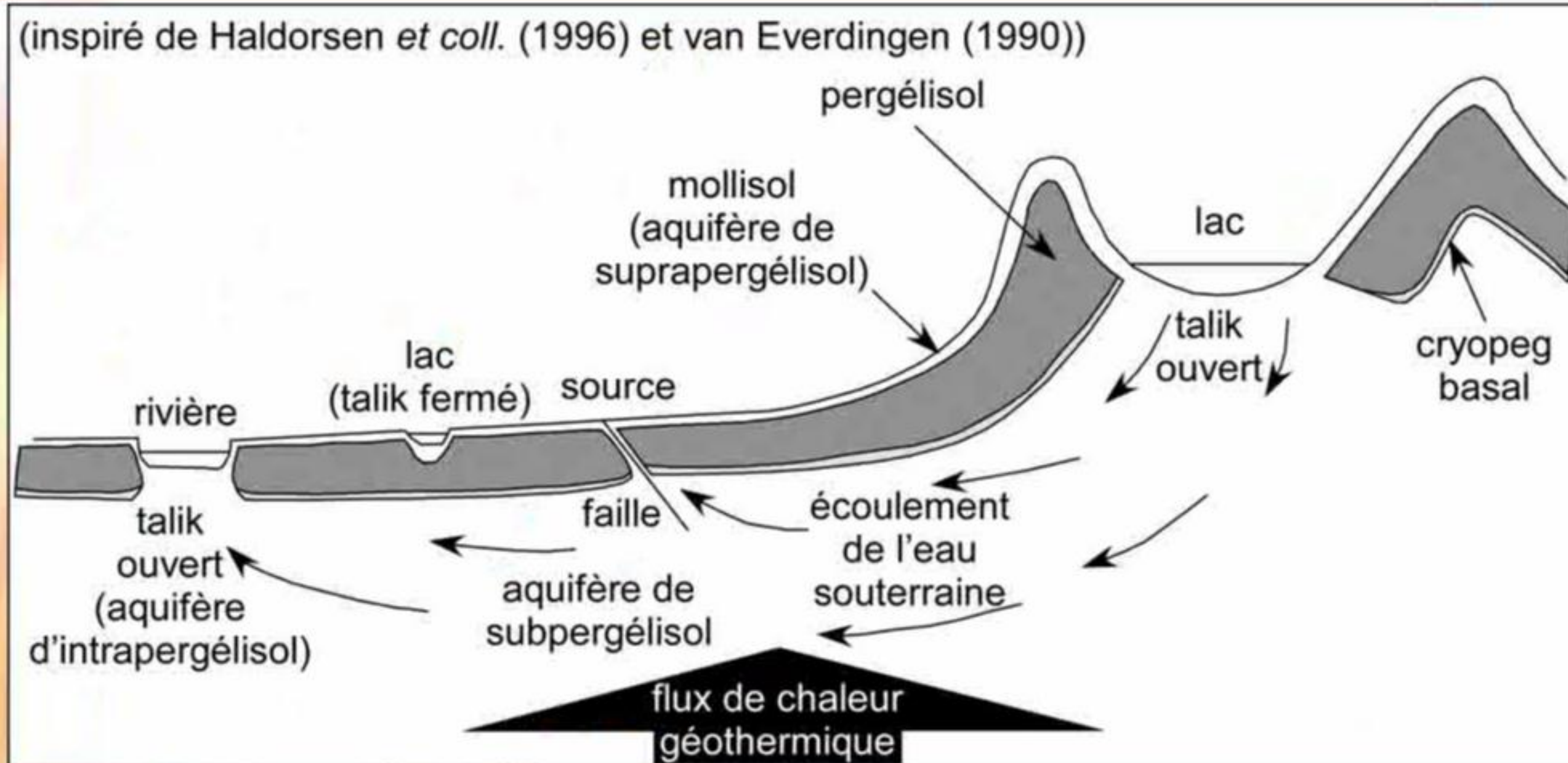


IKONOS satellite image
(SPACE IMAGING – July 26th 2005)
Image draping on a digital elevation model

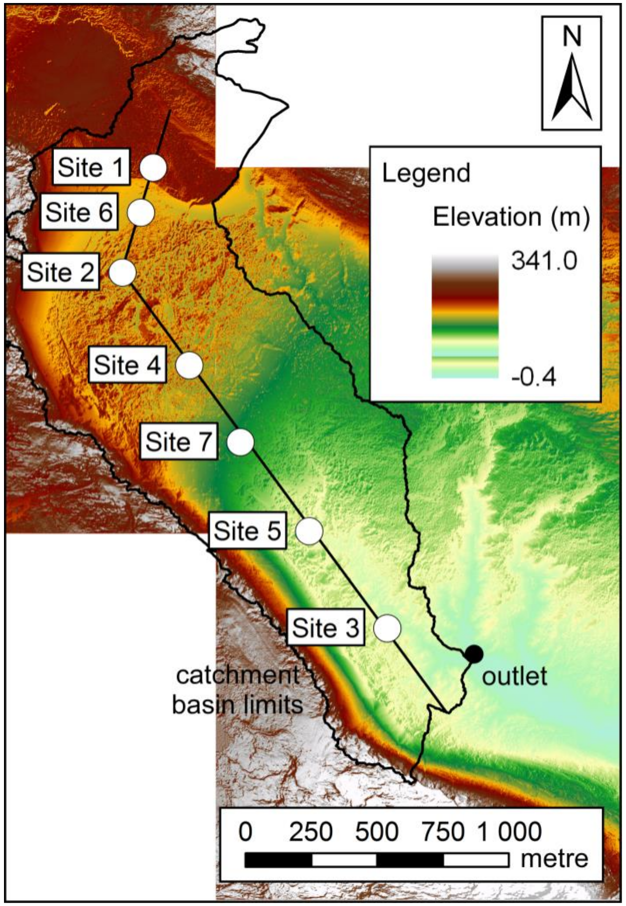
South oblique view
with artificial illumination

Vertical exaggeration 2:1

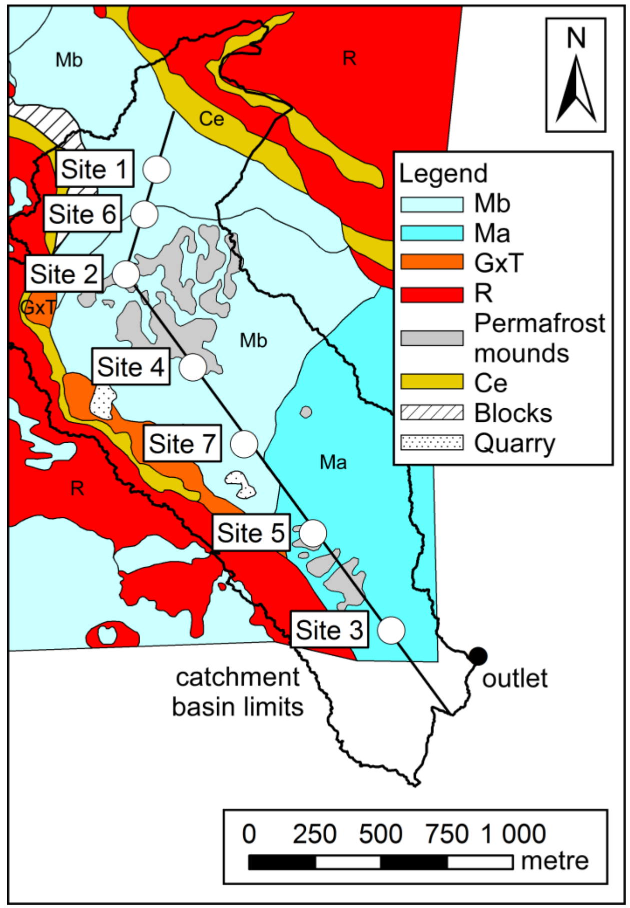
Le pergélisol: quelques concepts
(types d'aquifère en régions nordiques et talik ouvert ou fermé)



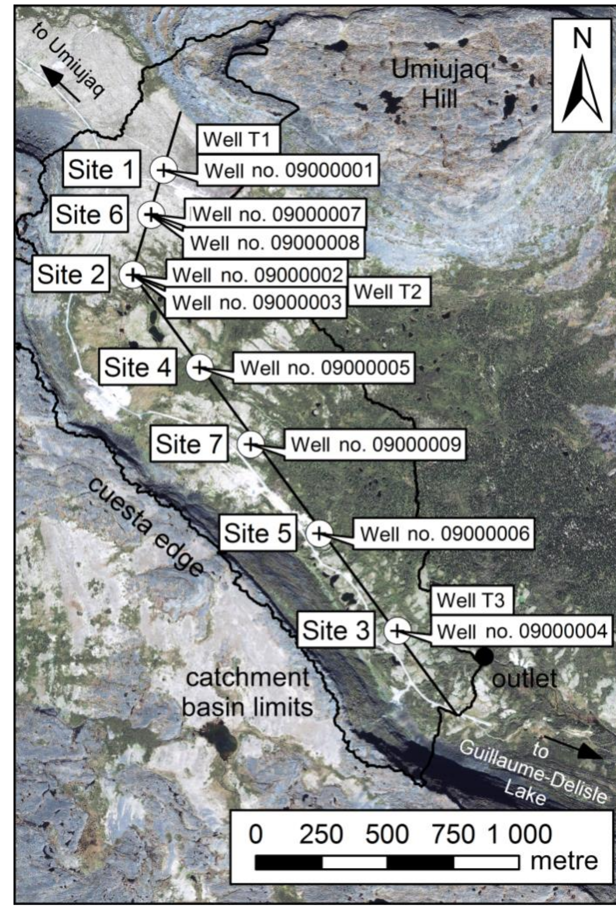
Site Description



LIDAR DEM

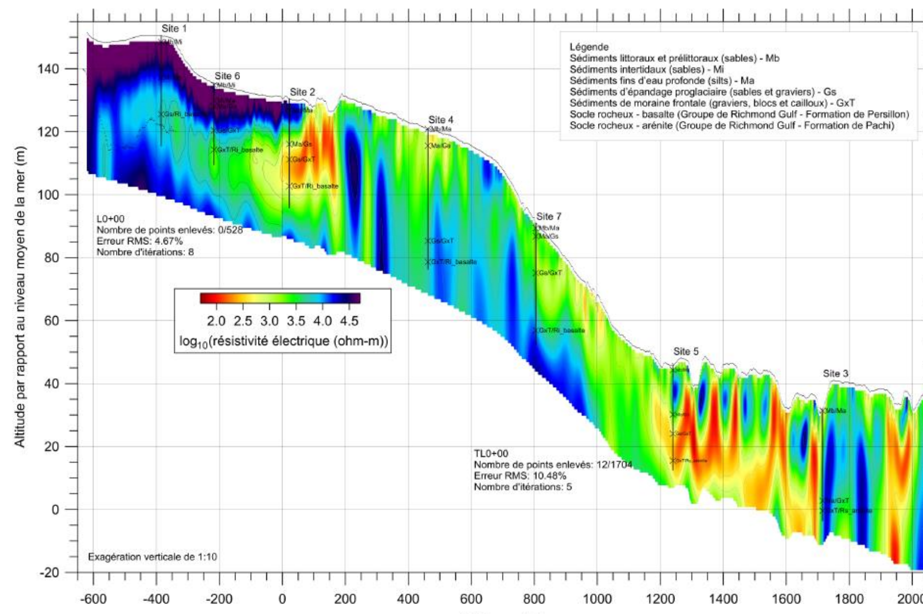


Surficial deposits

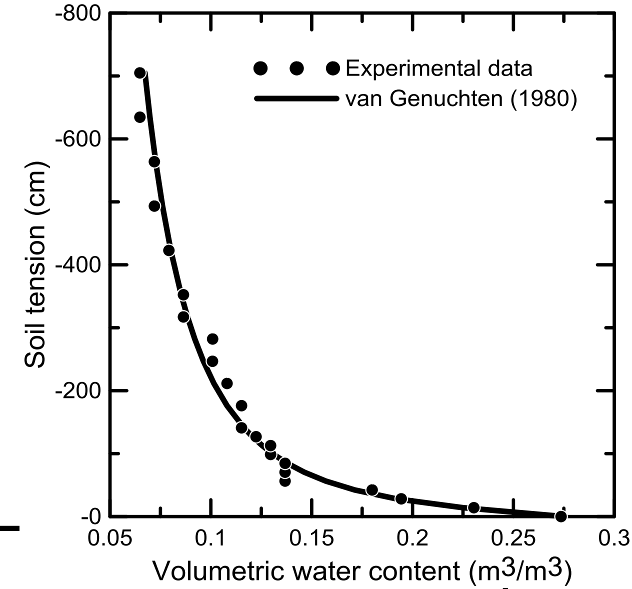


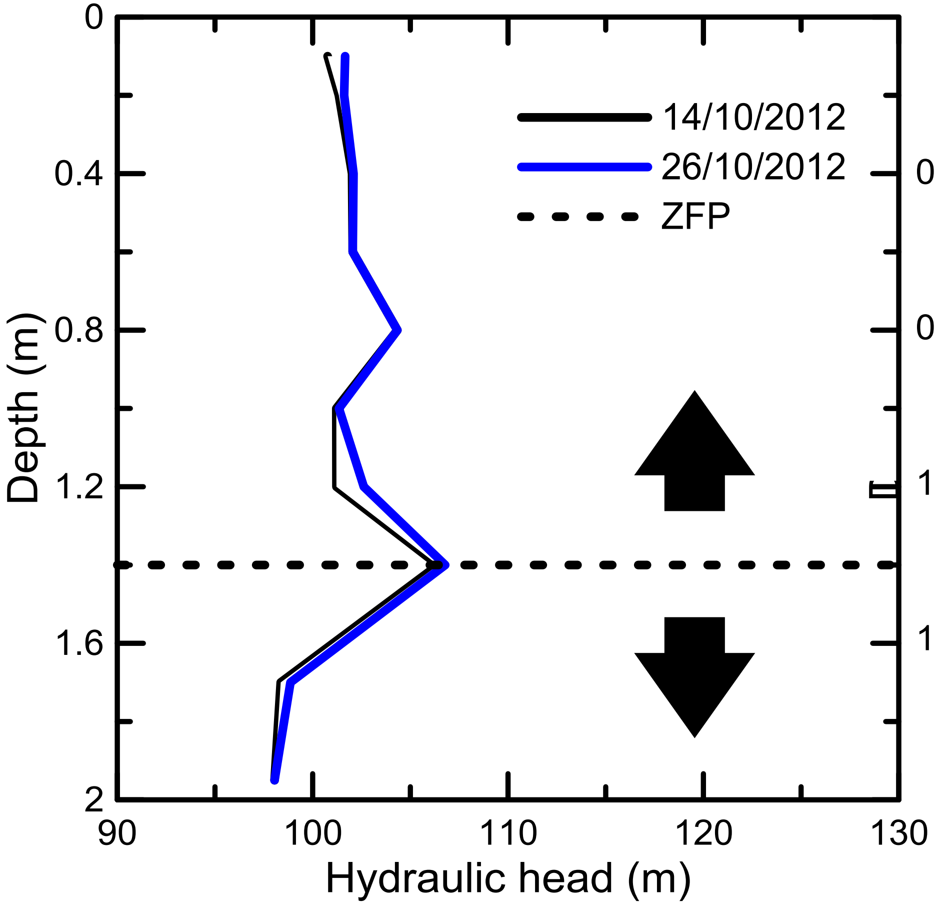
Wells location
Satellite image

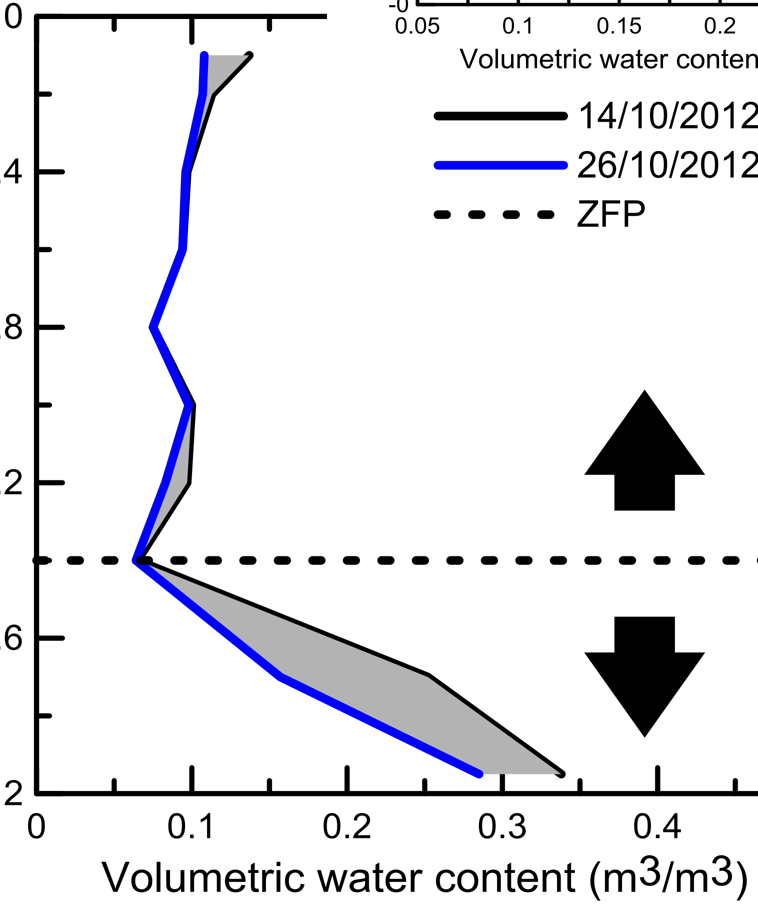
Basic site investigation



Recharge:
Zero flux plane method







Hydrocarbon Contamination in Fractured Rock at the Colomac Mine Site, NWT

Canada

Environment Canada

Greg Bickerton, Dale Van Stempvoort

Environment Canada

Water Science & Technology Directorate

Burlington, Ontario

UNIVERSITÉ LAVAL

Centre d'études nordiques

J. W. Molson

Canada Research Chair,

Quantitative Hydrogeology of Fractured Porous Media

Géologie & Génie Géologique

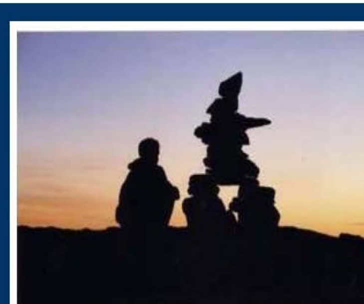
Université Laval, Quebec City

7th International Conference

Contaminants in Freezing Ground

May 24-28, 2010

Kingston, Ontario, Canada



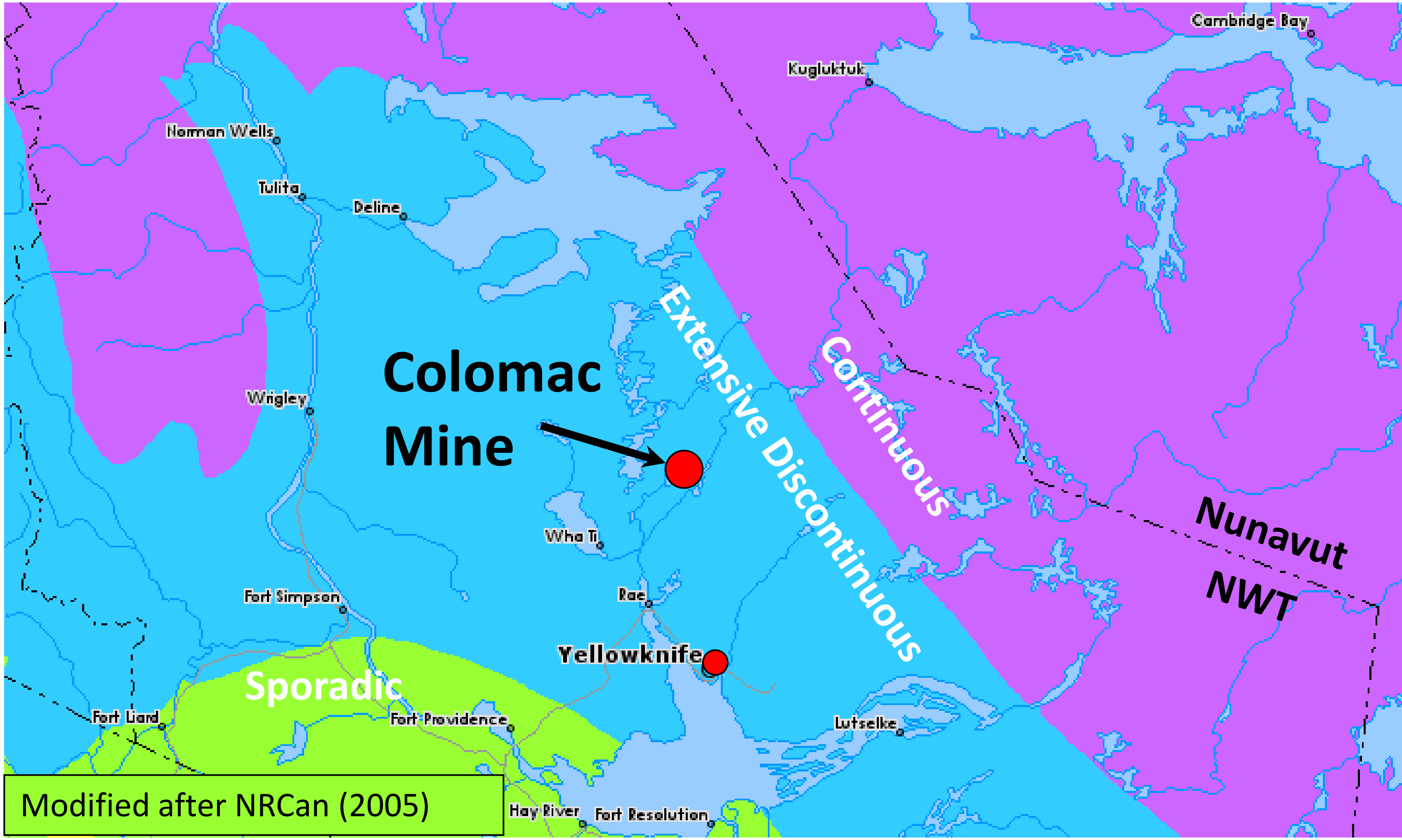
Interest in Northern Hydrogeology

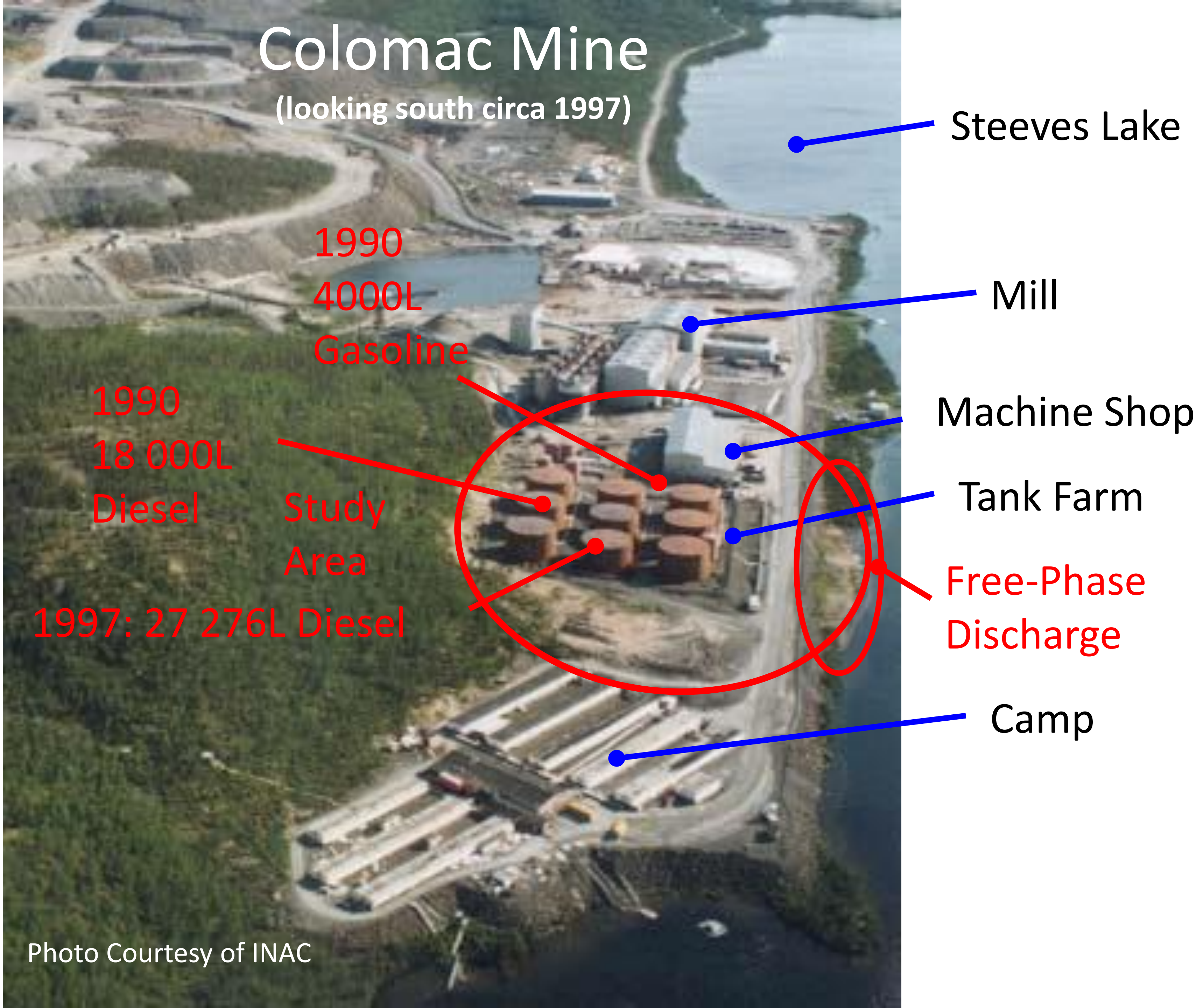
- Guidance on petroleum impacts in Canadian North
- Expanding resource activity & contaminated sites legacy
- Hydrogeological knowledge gap in cold-climate regions
- Role of permafrost & seasonal active layer on groundwater

Colomac Mine (2005)


Colomac Mine
Yellowknife
Quebec City
Ottawa
Kingston
Modified after Google Earth (2007)

Canadian Permafrost Zones




Colomac Mine
(looking south circa 1997)
Steeves Lake
Mill
Machine Shop
Tank Farm
Free-Phase Discharge
Camp
1990
4000L
Gasoline
1990
18 000L
Diesel
Study Area
1997: 27 276L Diesel
Photo Courtesy of INAC

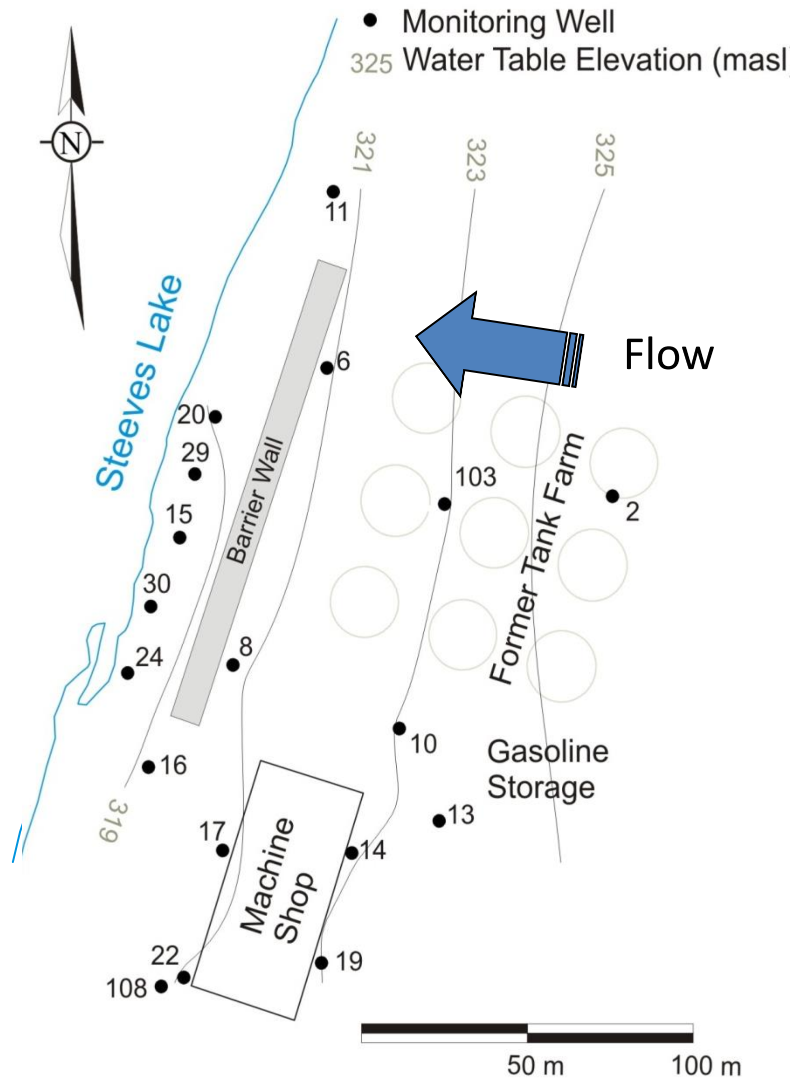
Objectives

- Characterize fractured bedrock permeability & contaminant distribution
- Document dynamics of subsurface thermal regime
- Explore geochemical evidence for intrinsic bioremediation
- Refine conceptual model of local groundwater system

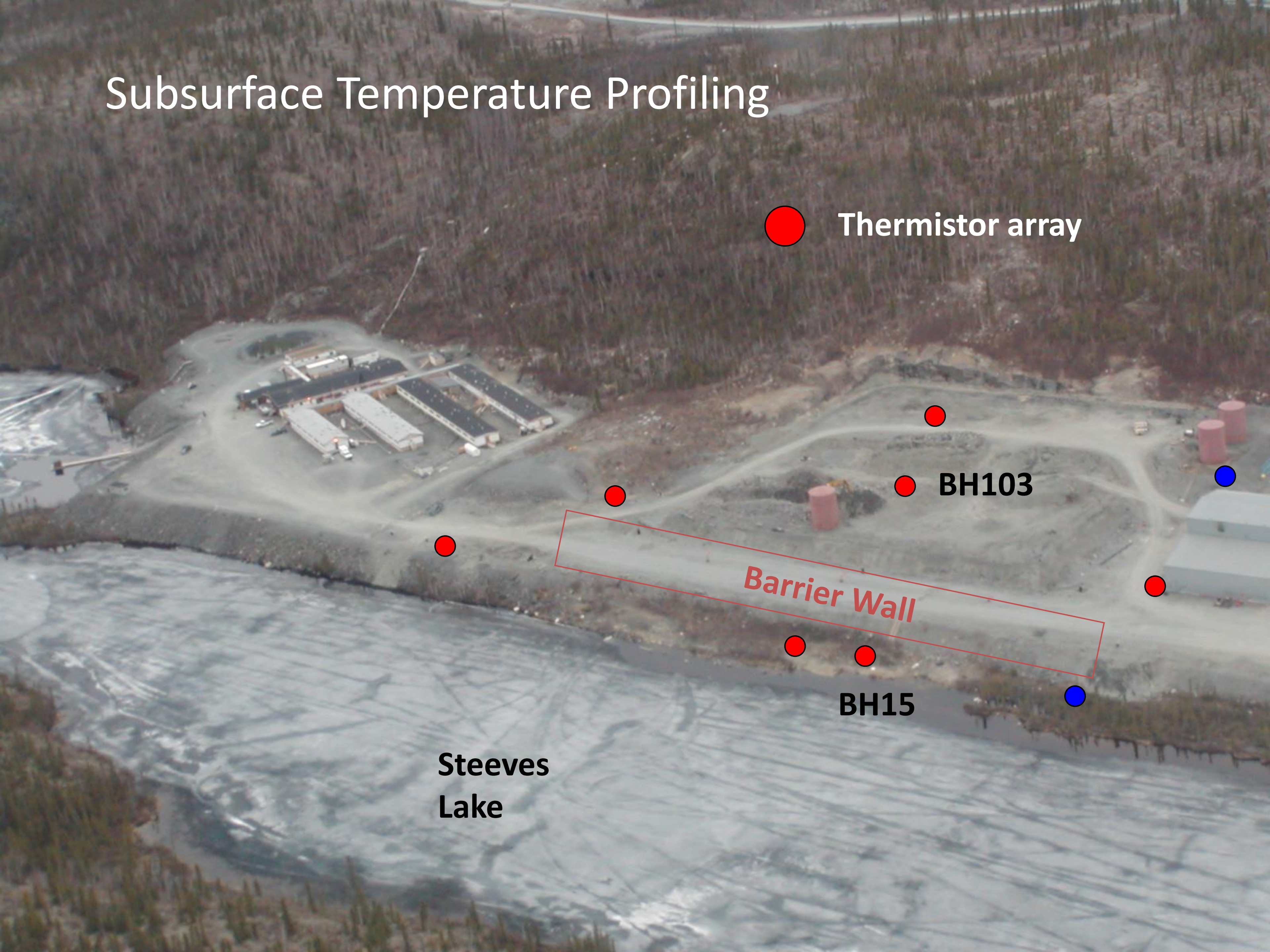
Colomac Mine (2005)

Monitoring Network

- 33 bedrock monitoring boreholes
- 10 thermistor arrays to 15 m depth
- 3 thermistor arrays at base of barrier wall

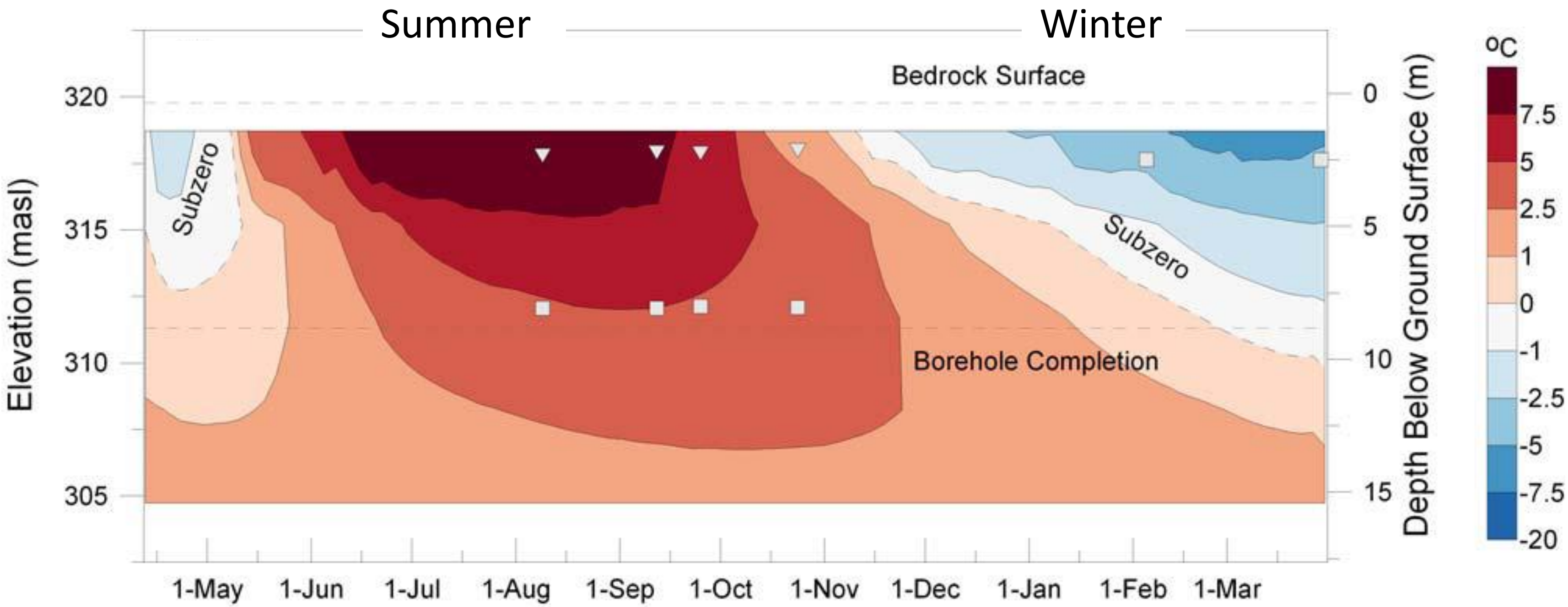


Subsurface Temperature Profiling



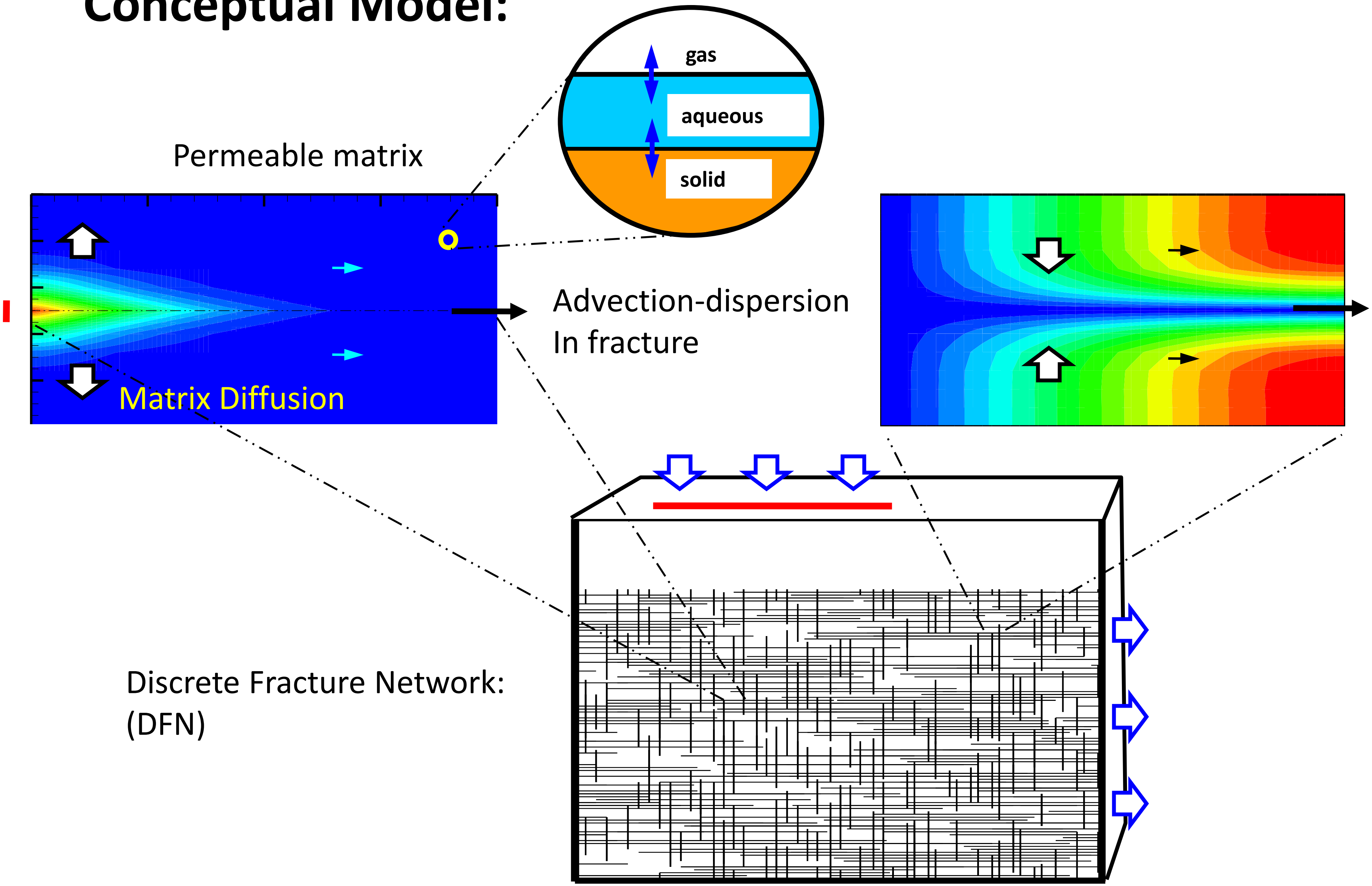
Subsurface Temperature Profiling

BH15 (Shoreline)



April 12, 2006 to March 30, 2007

Conceptual Model:

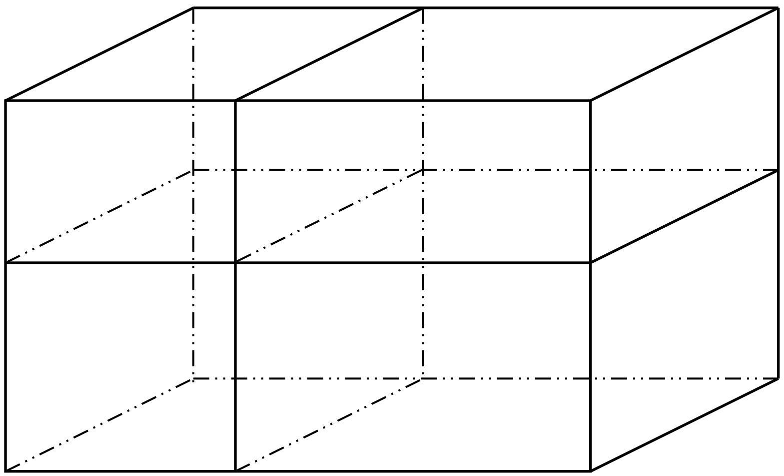


Numerical Simulation Approach:

HEATFLOW/SMOKER Model (Molson & Frind 2009)

3D Porous Matrix:

$$\frac{\partial}{\partial x_i}\left[\left(\kappa + \frac{D_{ij}}{R}\right)\frac{\partial T}{\partial x_j}\right] - \frac{\partial}{\partial x_i}\left(\frac{v_i}{R}T\right) = \frac{\partial T}{\partial t}$$

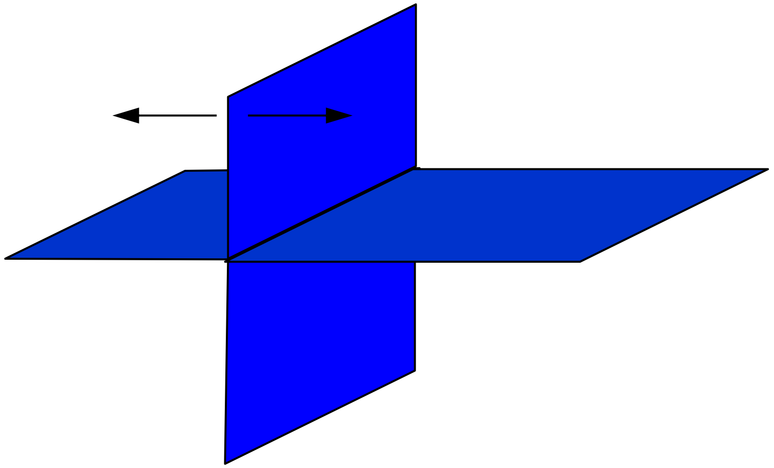


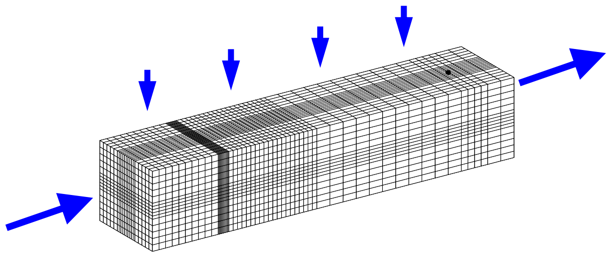
2D Fractures:

$$\frac{\partial}{\partial x_i}\left(D'_{ij}\frac{\partial T'}{\partial x_j}\right) - \bar{v}_i\frac{\partial T'}{\partial x_i} - \frac{D'_{ij}}{b}\left[\frac{\partial T'}{\partial z}\right]_{z=\pm b} = \frac{\partial T'}{\partial t}$$

Fracture velocities:

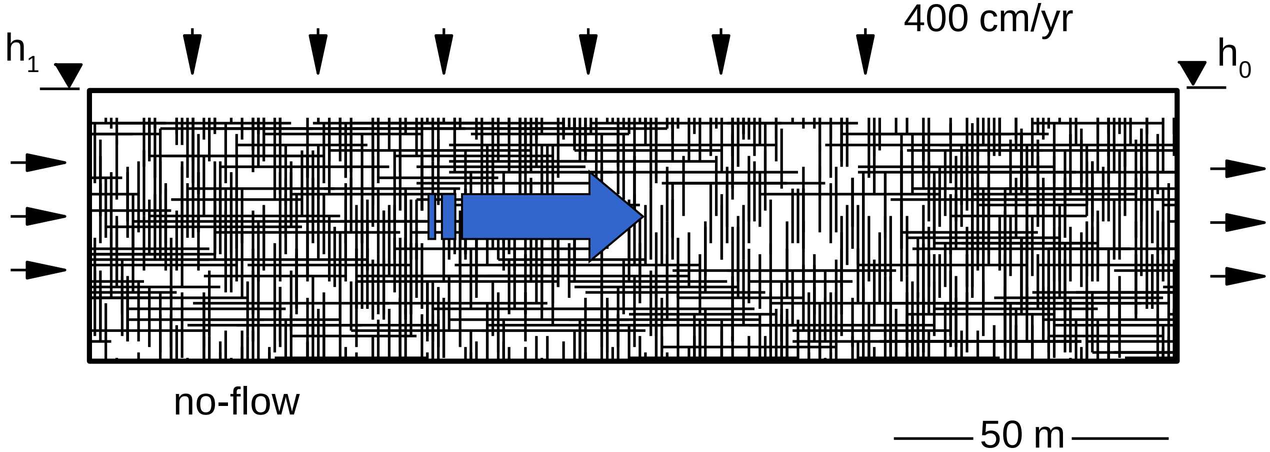
$$\bar{v} = \frac{-(2b)^2}{12\mu}\rho g \nabla h$$

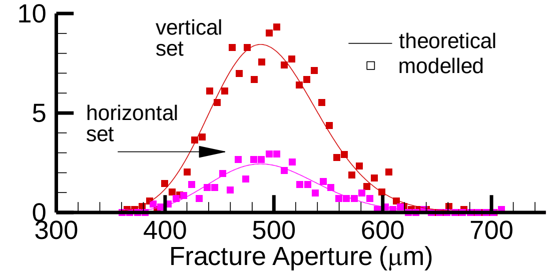




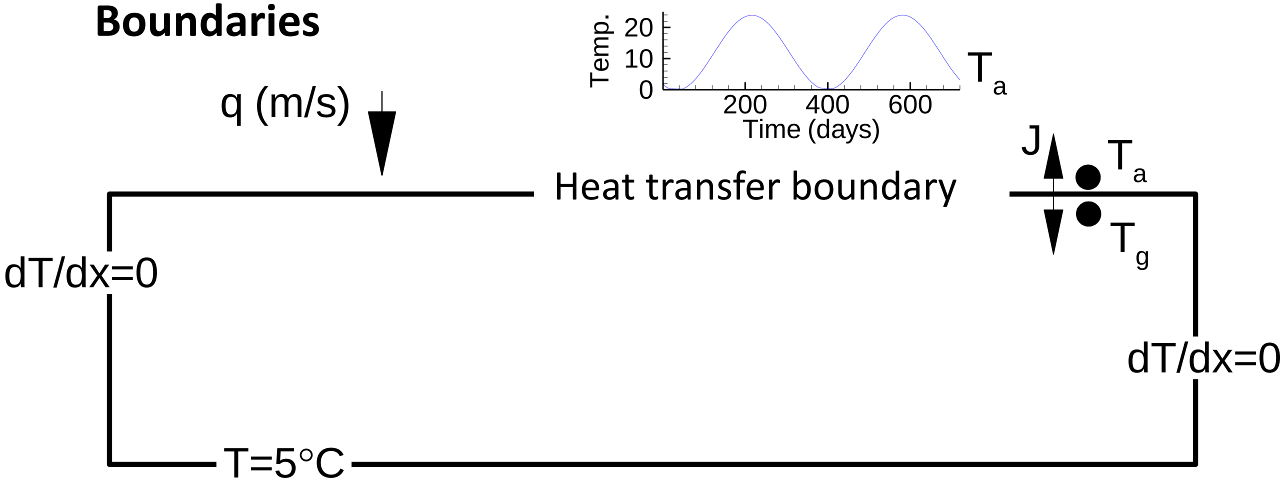
Natural Thermal Source Model

Flow Boundaries:

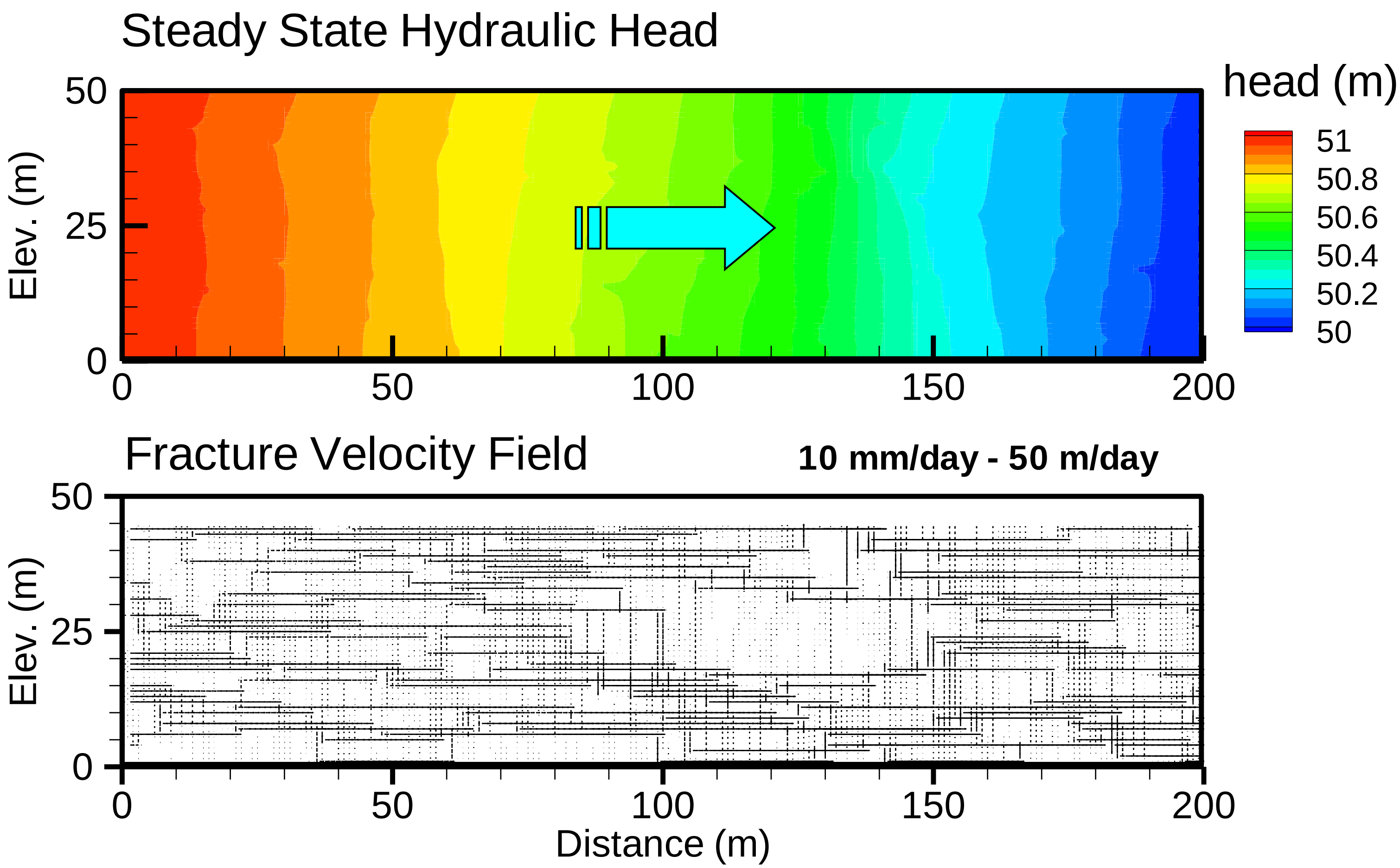




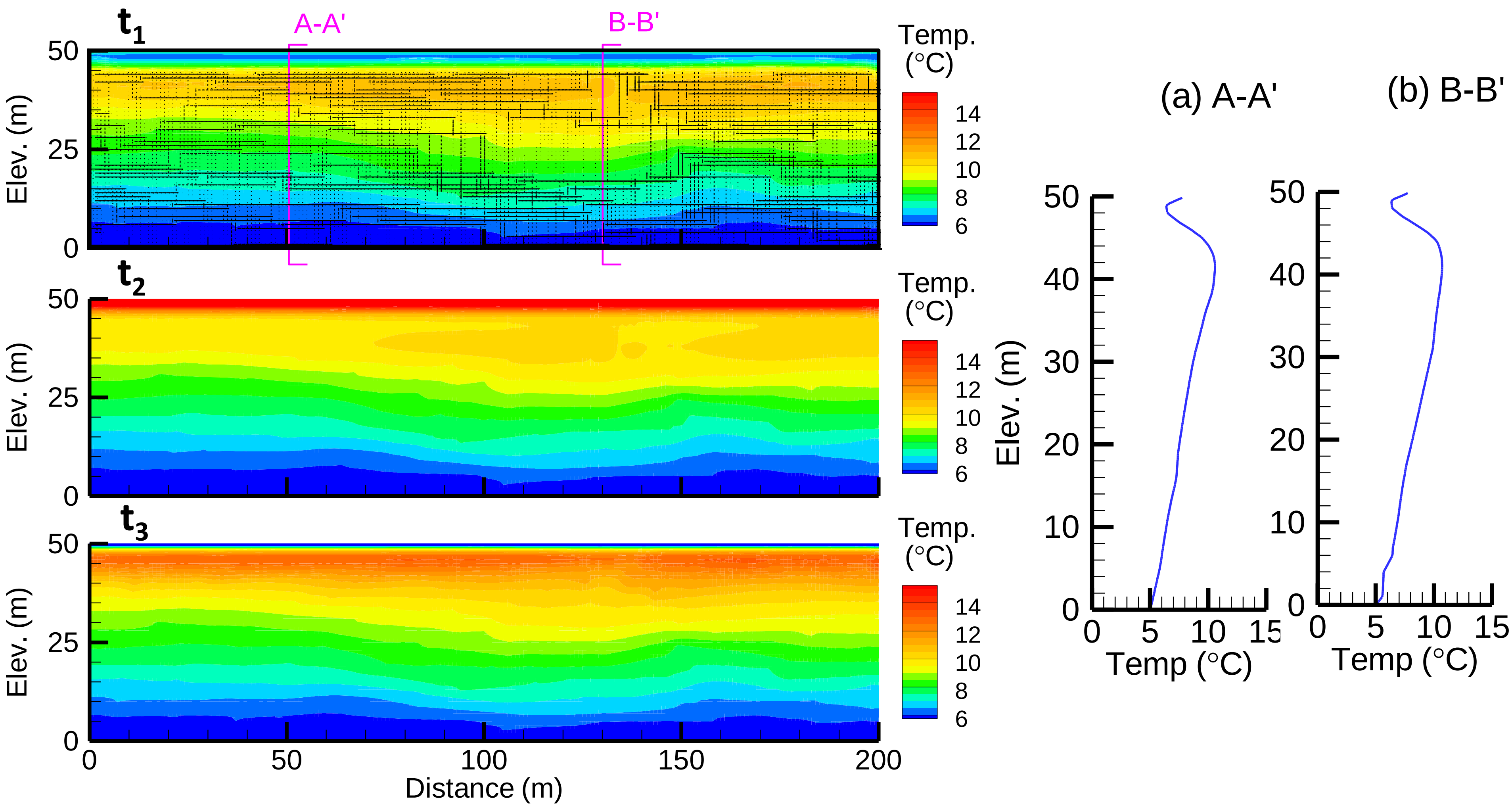
Thermal Transport Boundaries



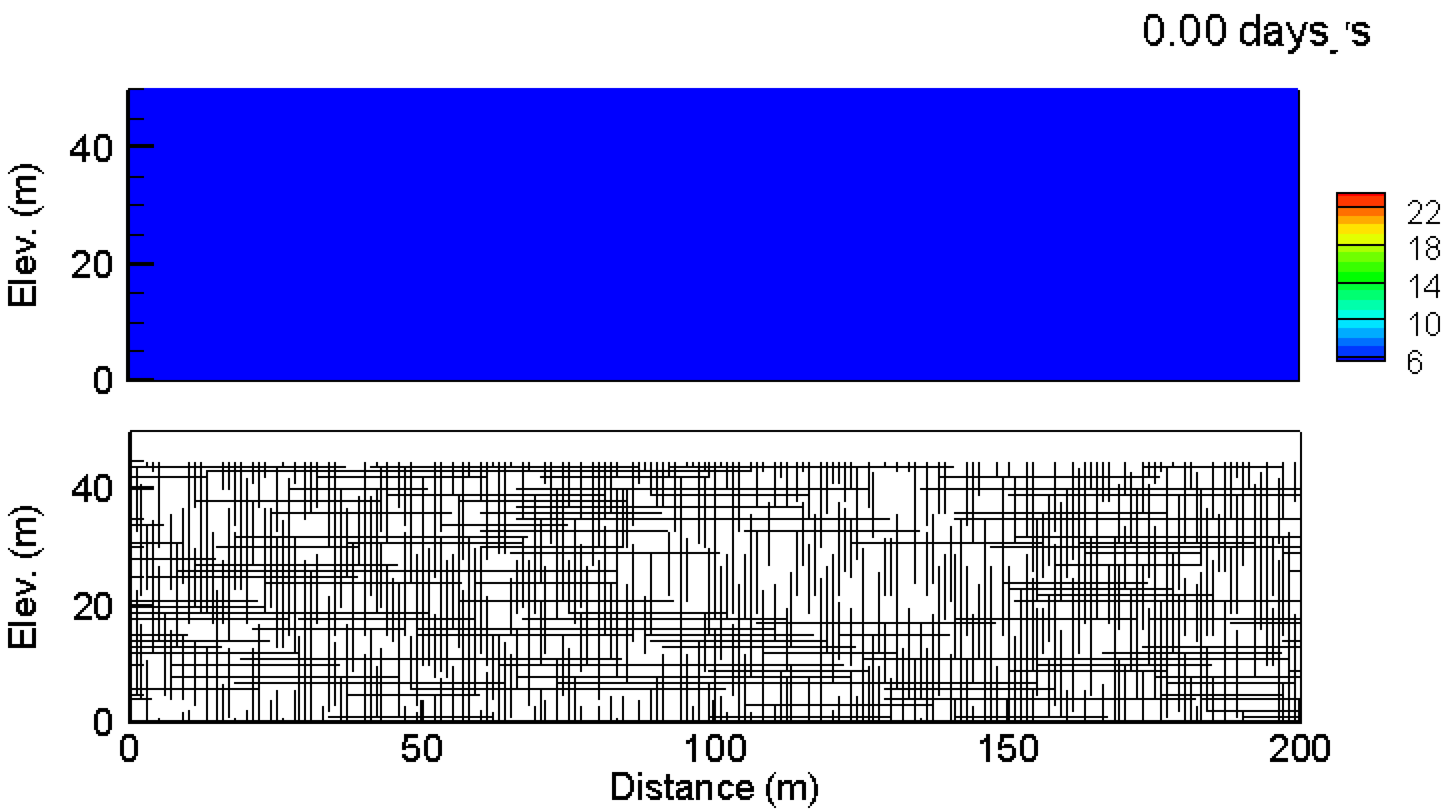
Flow Simulation



Simulated Temperature Distributions ($\overline{2b}$=500µm)

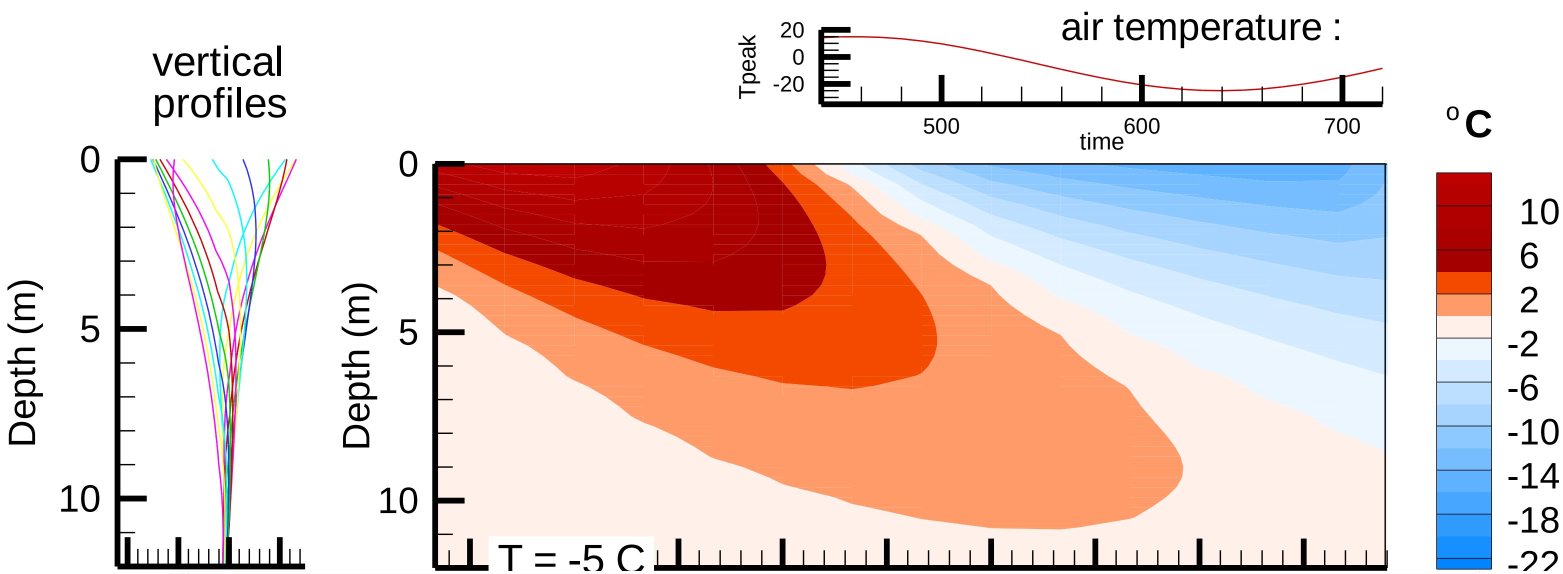


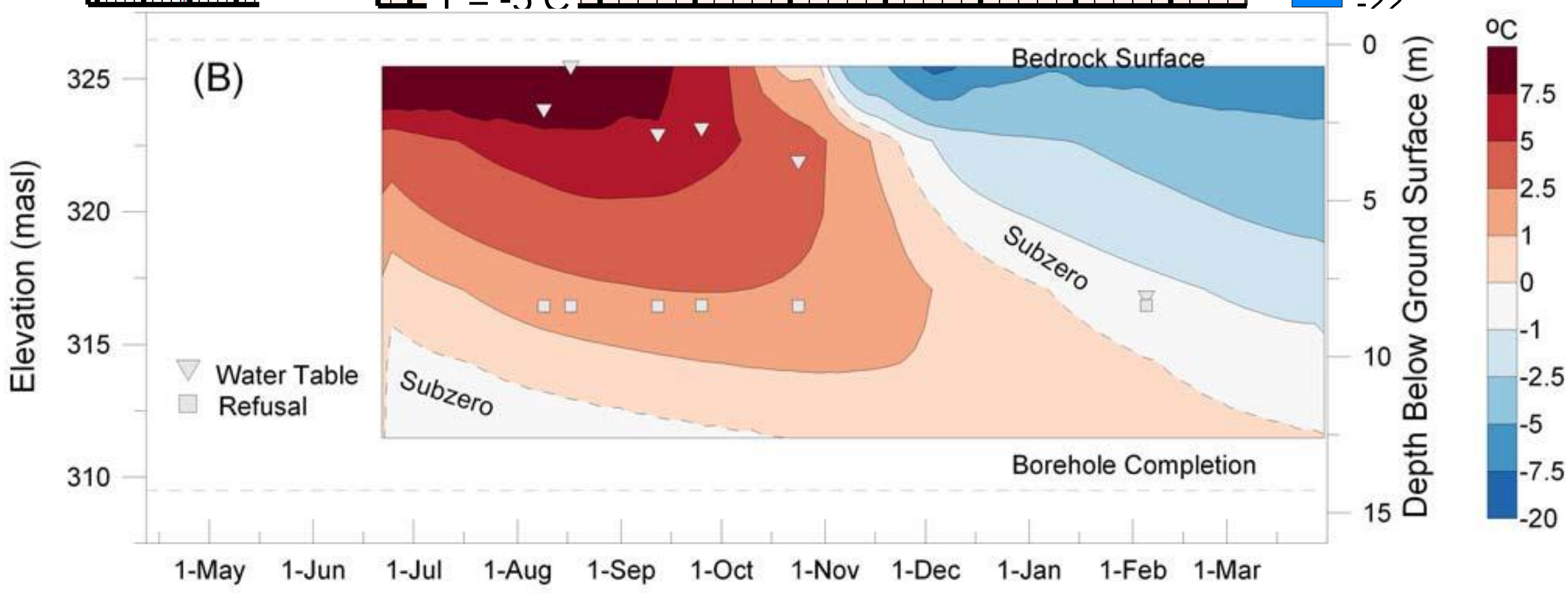
Heatflow Simulation:
Surface Temperature Source



Simulated Subsurface Temperature Profiles

Heatflow model (Molson & Frind, 2009)





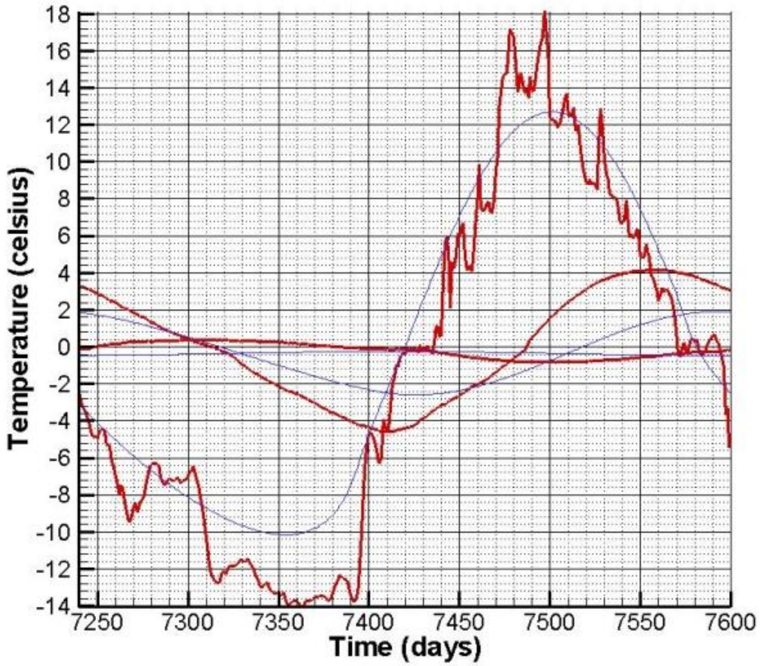
Simulated temperature profiles: Colomac site

Conduction only, no flow

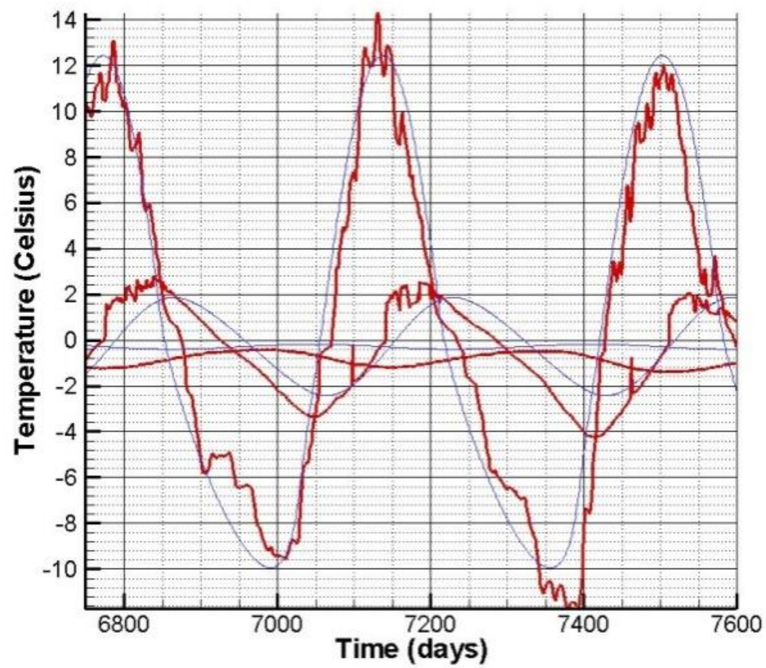
Observed

Simulated

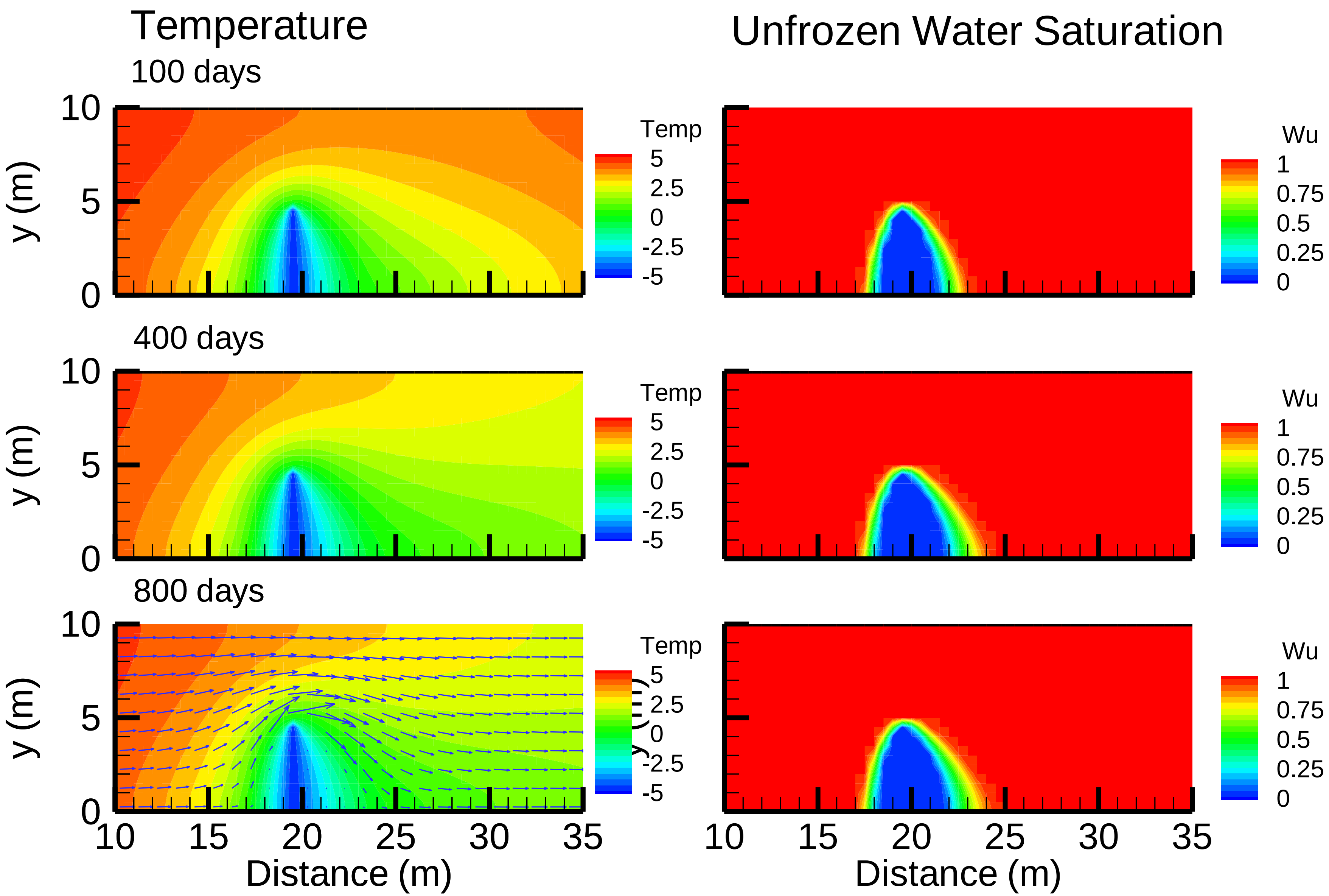
Well 2



Well 13

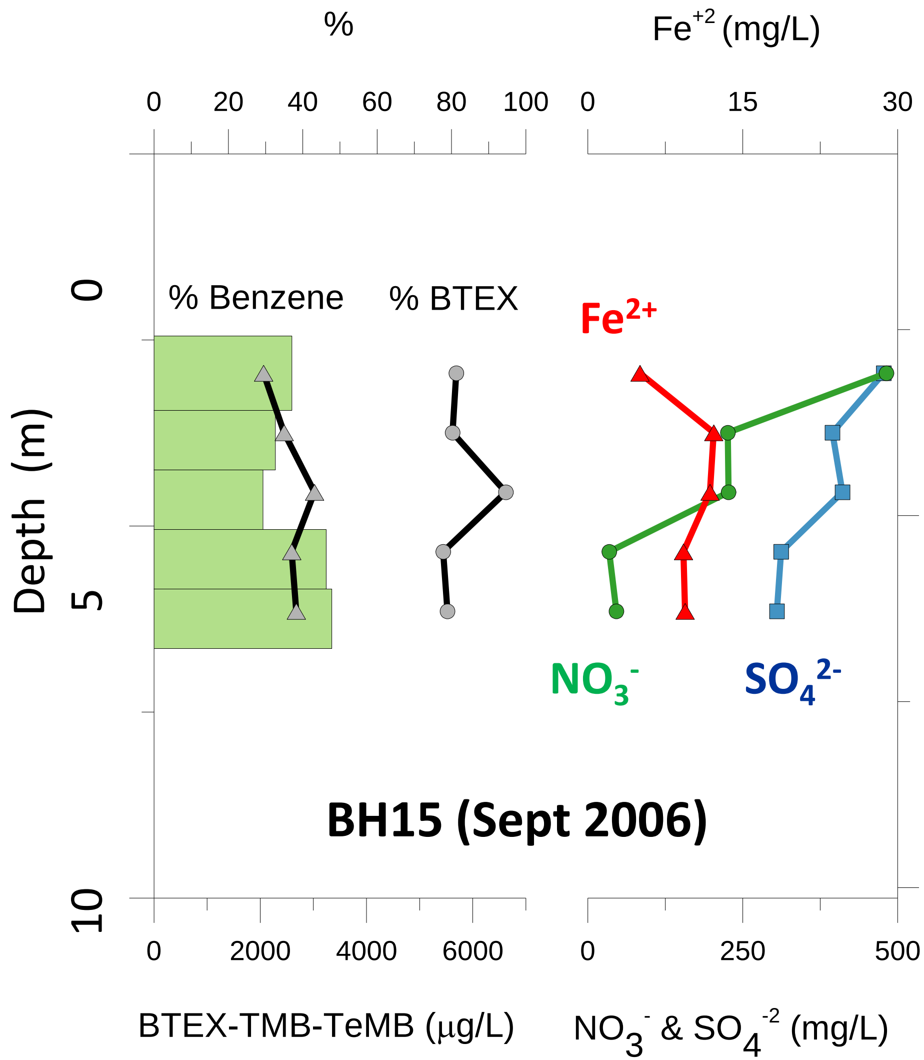


HEATFLOW Model: 3D Ice Wall Numerical Simulation



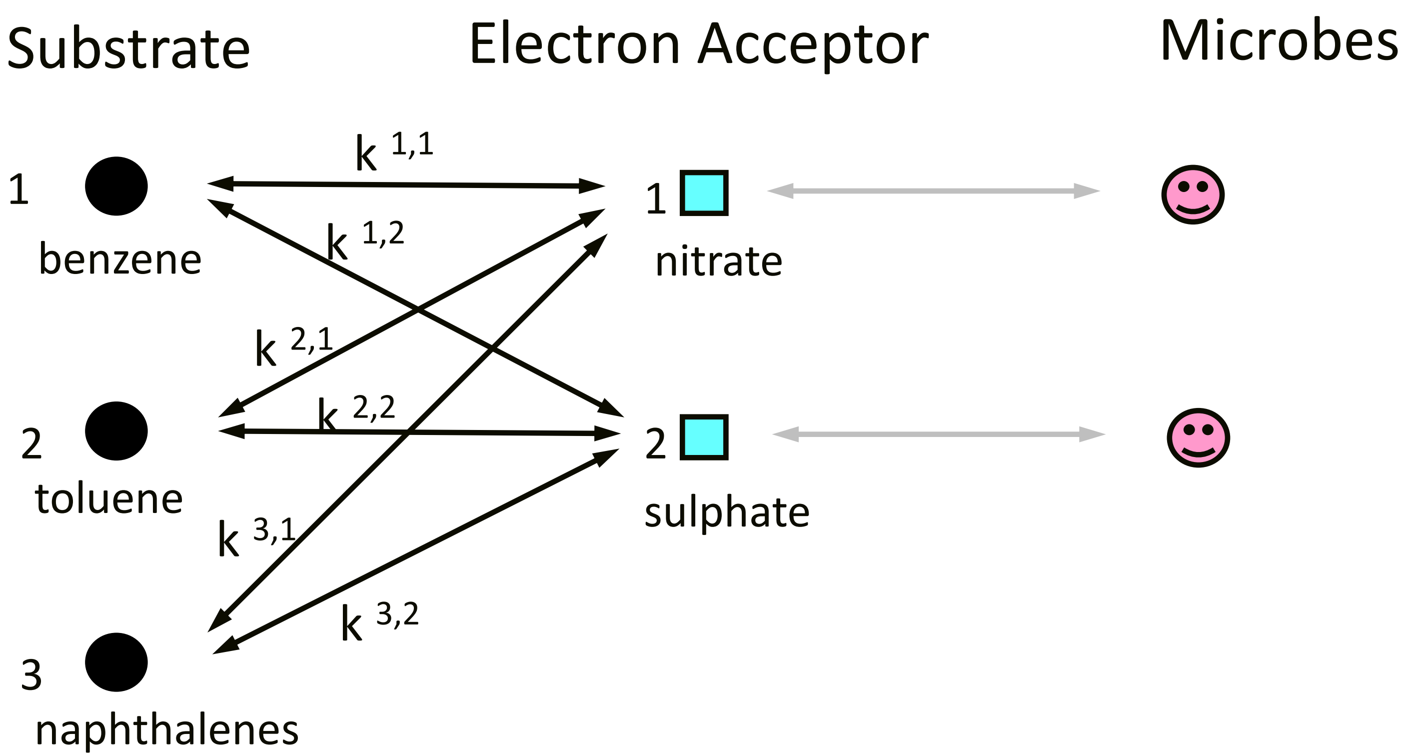
Groundwater Geochemistry

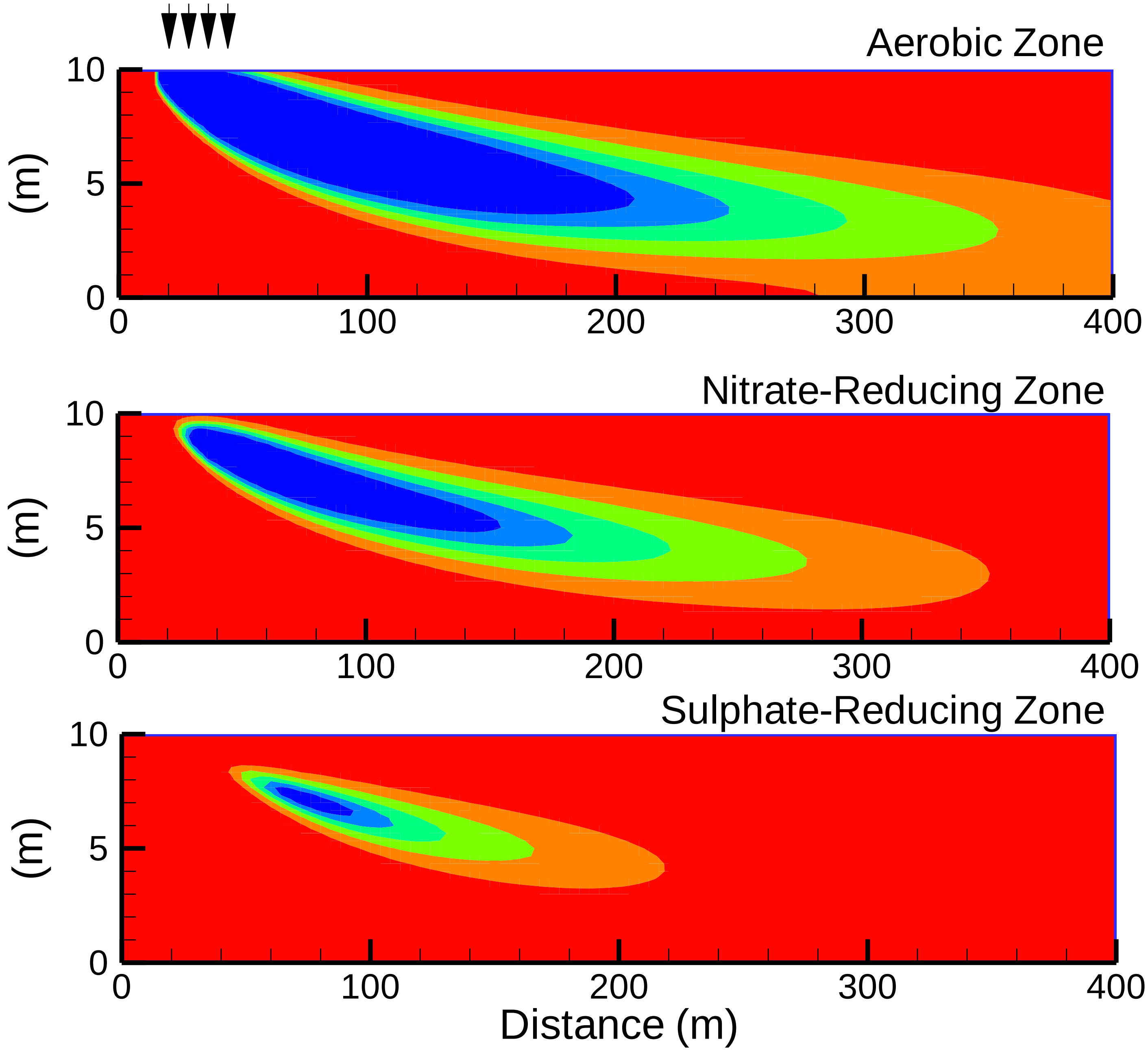
- Discrete samples from features identified in permeability profiling
- Petroleum impacts in most wells
- Uniform inorganic chemistry observed
- Volatile fatty acids suggest intrinsic bioremediation occurring



Substrate/Electron Acceptor/Microbe Coupling
BIONAPL / 3D

$$\frac{\partial C^{\alpha}}{\partial t} R = \frac{\partial}{\partial x_i}\left[D_{ij} \frac{\partial C^{\alpha}}{\partial x_j} \right] - v_i \frac{\partial C^{\alpha}}{\partial x_i} + \lambda^{\alpha}_{DIS}\left(C_S - C^{\alpha} \right) - \lambda^{\alpha}_{BIO} C^{\alpha}$$

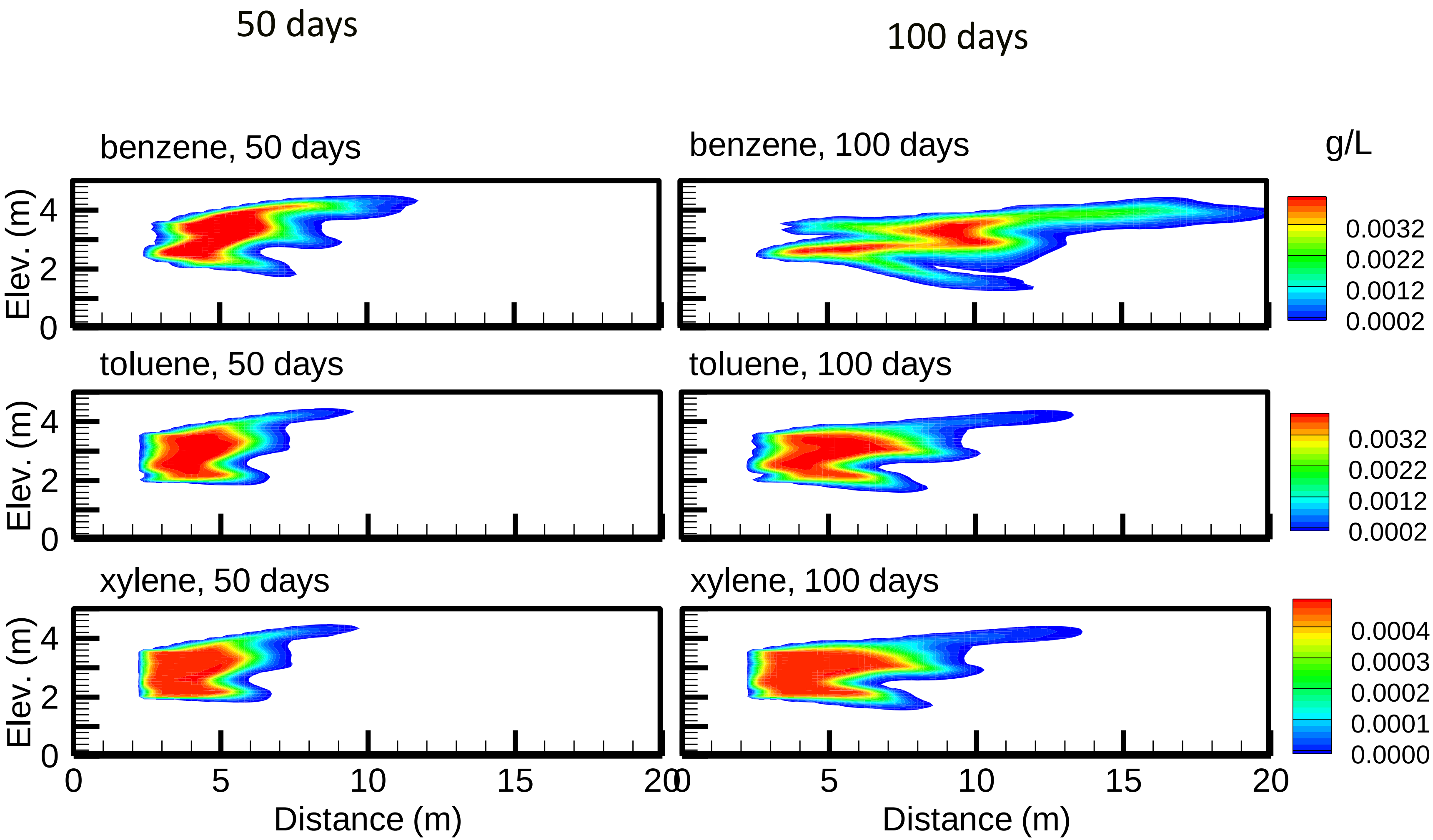




Aerobic Zone
Nitrate-Reducing Zone
Sulphate-Reducing Zone
(m)
10
5
0
0
100
200
300
400
Distance (m)

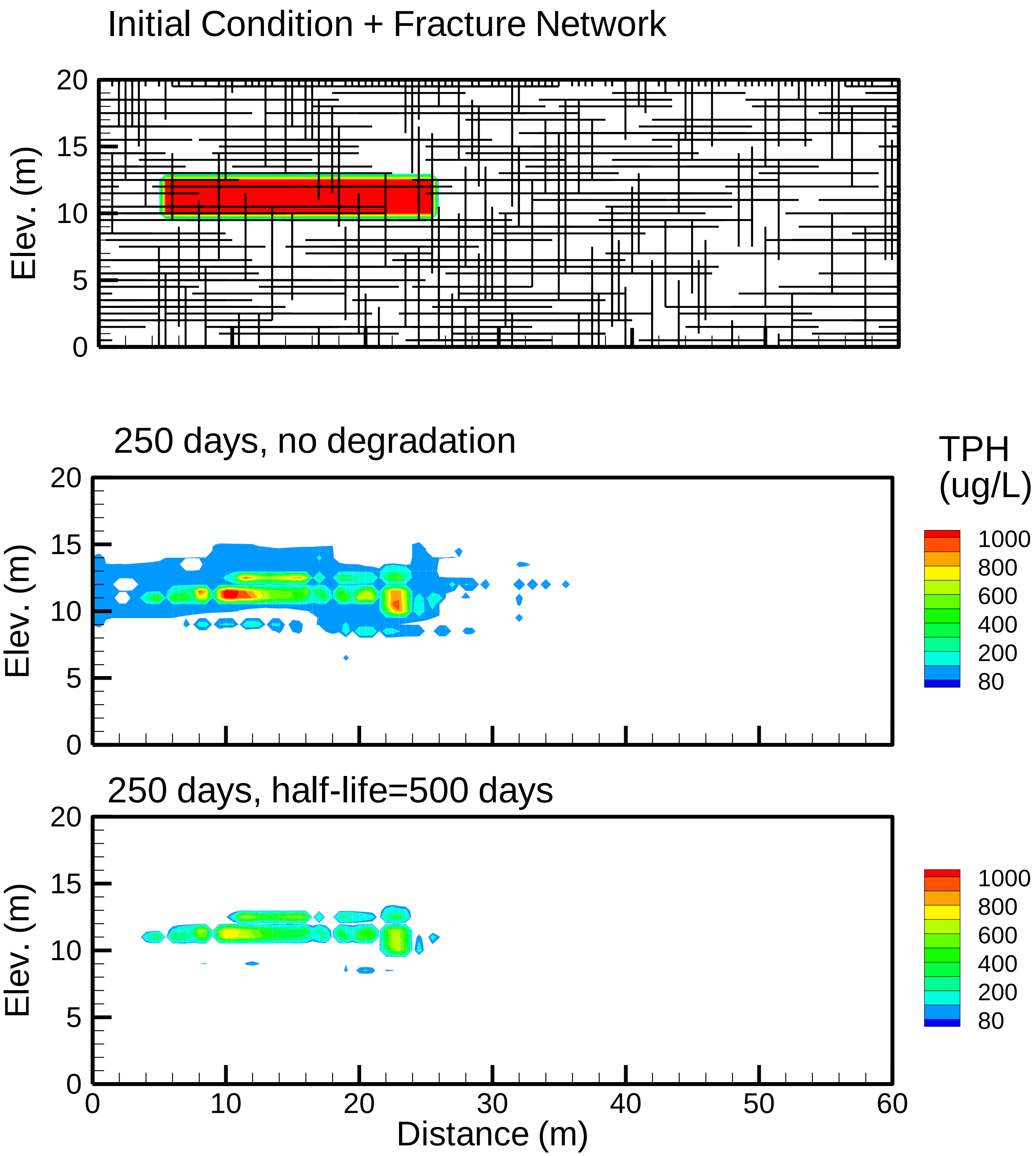
Simulated Gasoline Spill

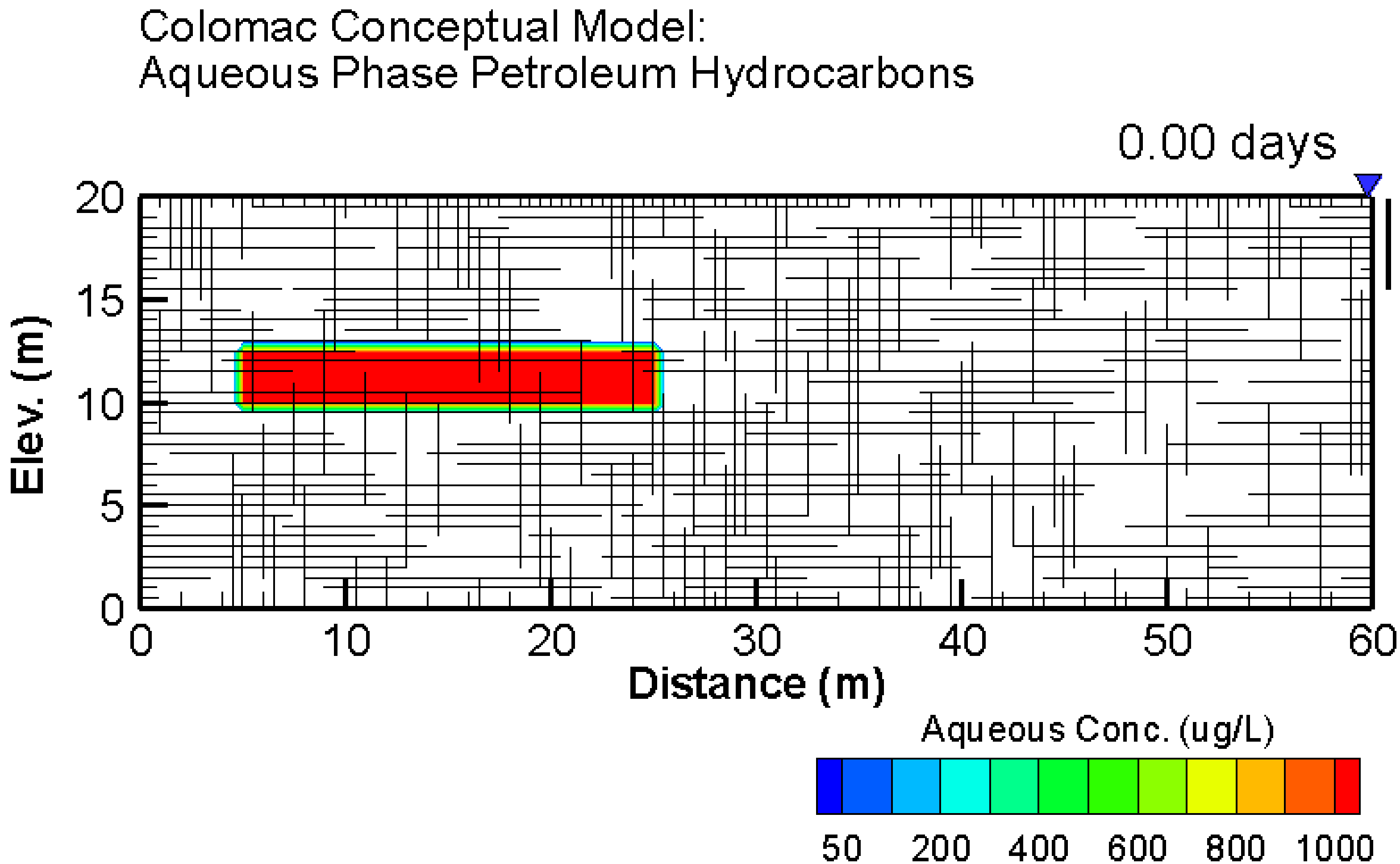
Heterogeneous Porous medium: Realization 5



Simulated Gasoline Spill

Fractured Porous Medium

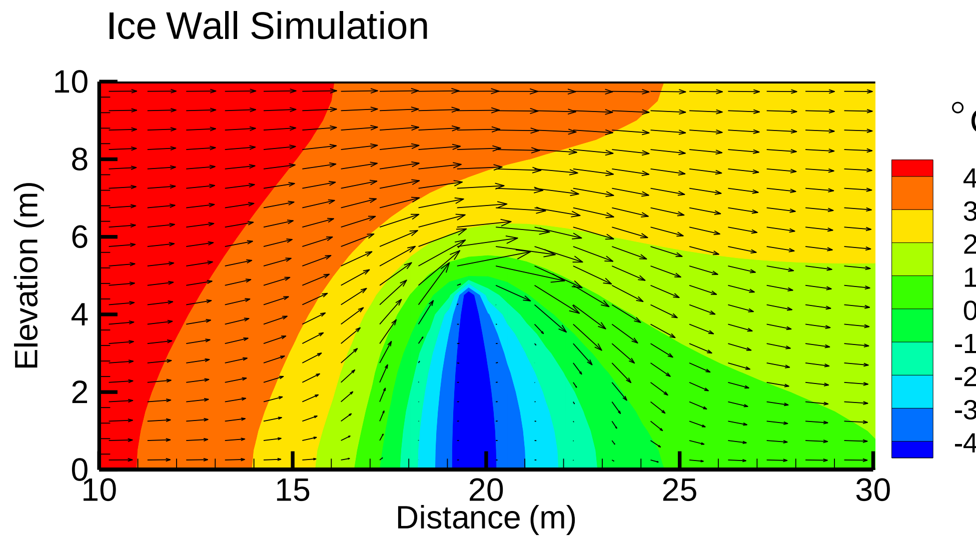




Colomac Conceptual Model:
Aqueous Phase Petroleum Hydrocarbons
0.00 days
Elev. (m)
0
5
10
15
20
Distance (m)
0
10
20
30
40
50
60
Aqueous Conc. (ug/L)
50
200
400
600
800
1000

Summary

- Seasonal dimension to groundwater system but deeper portions always active
- Absence of permafrost above 15 m depth
- Indicators of intrinsic bioremediation present



Colomac Mine (2007)

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NSERC CRSNG

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