Numerical Modelling of Deep Permafrost-Impacted Groundwater Flow Systems under Climate Change:

PhD student: Mahsa Malmir

Mahsa.malmir.1@ulaval.ca

Supervisors: J. Molson PhD. Ing.

R. Therrien PhD. Ing.

Uncertainties and knowledge gaps relevant to NWMO's mandate:

Effect of permafrost freeze/thaw cycles on:

- Deep density-dependent flow systems over ~10^6 years
- Radionuclide migration from a DGR
- Flow within a discretely fractured system

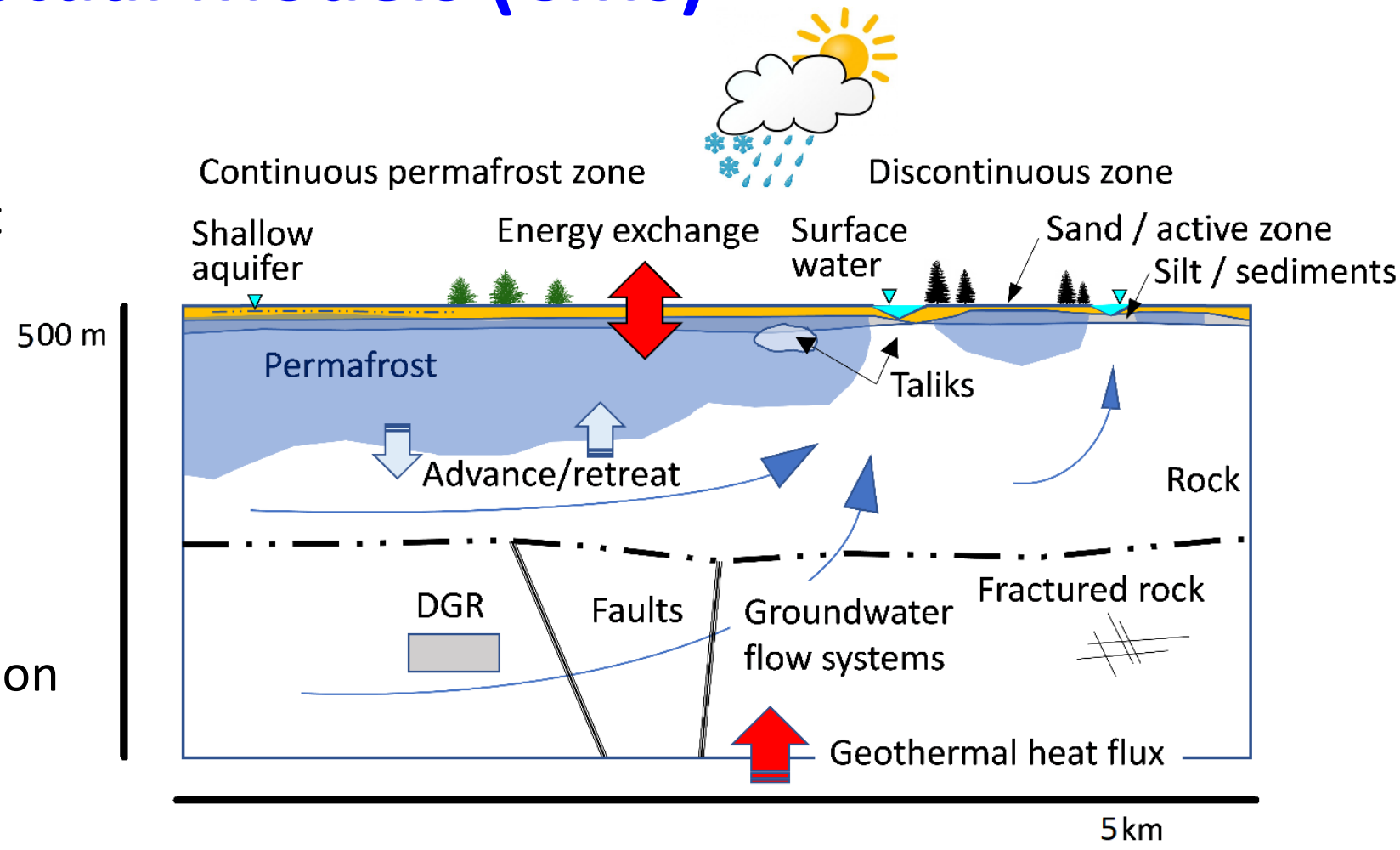
nwmo
NUCLEAR WASTE MANAGEMENT ORGANIZATION

Research Goals

- Effect of permafrost growth and thaw
- Investigate the effect of permafrost extension to DGR depths
- Importance of groundwater flow including dense brine
- Compare a discretely fractured network (DFN) system to an equivalent porous medium (EPM)
- System behavior over long time scales (10^6 yrs)

Conceptual Models (CMs)

- CM 1:
  Generic large-scale systems: Groundwater flow, permafrost freeze/thaw, brine transport
- CM 2:
  Climate change: glacial cycles
- CM 3:
  DGR heating loads and migration pathways
- CM 4:
  Discretely-fractured porous rock

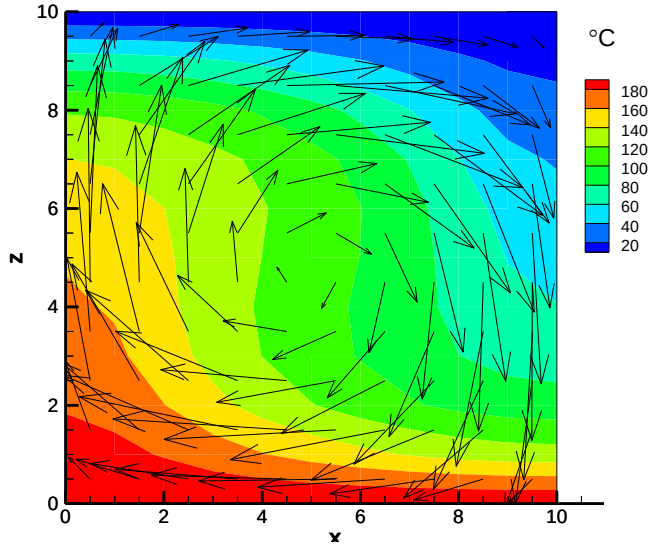


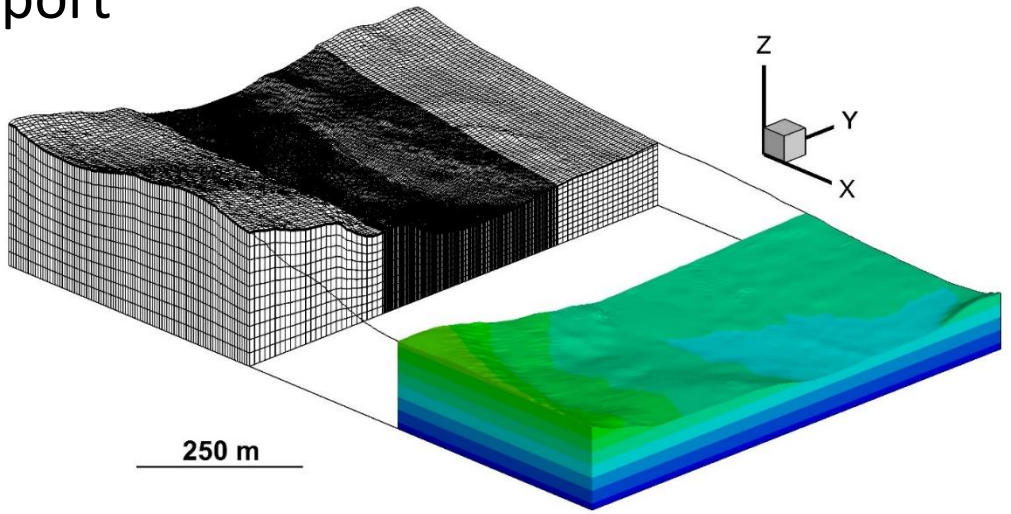
2D/3D Numerical Modelling Approaches

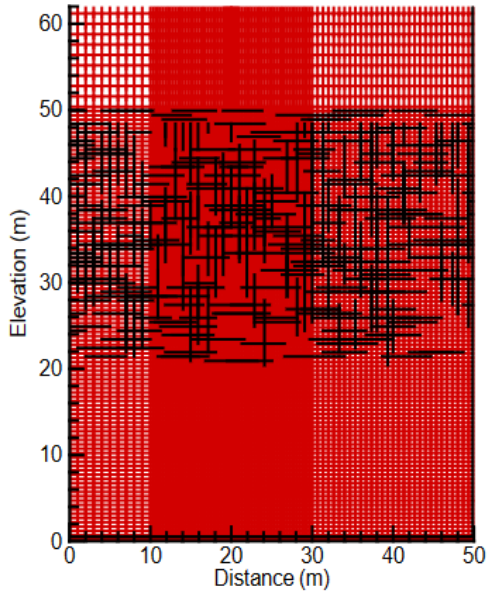
HEATFLOW-SMOKER (Molson & Frind, 2021)

HYDROGEOSPHERE (Aquanty Inc, 2018):

- 3D finite element / finite volume
- Density-dependent flow
- Coupled heat, mass & age transport
- Discrete fractures
- Surface energy balance
- Freeze/thaw, latent heat
  (Heatflow/Smoker only)



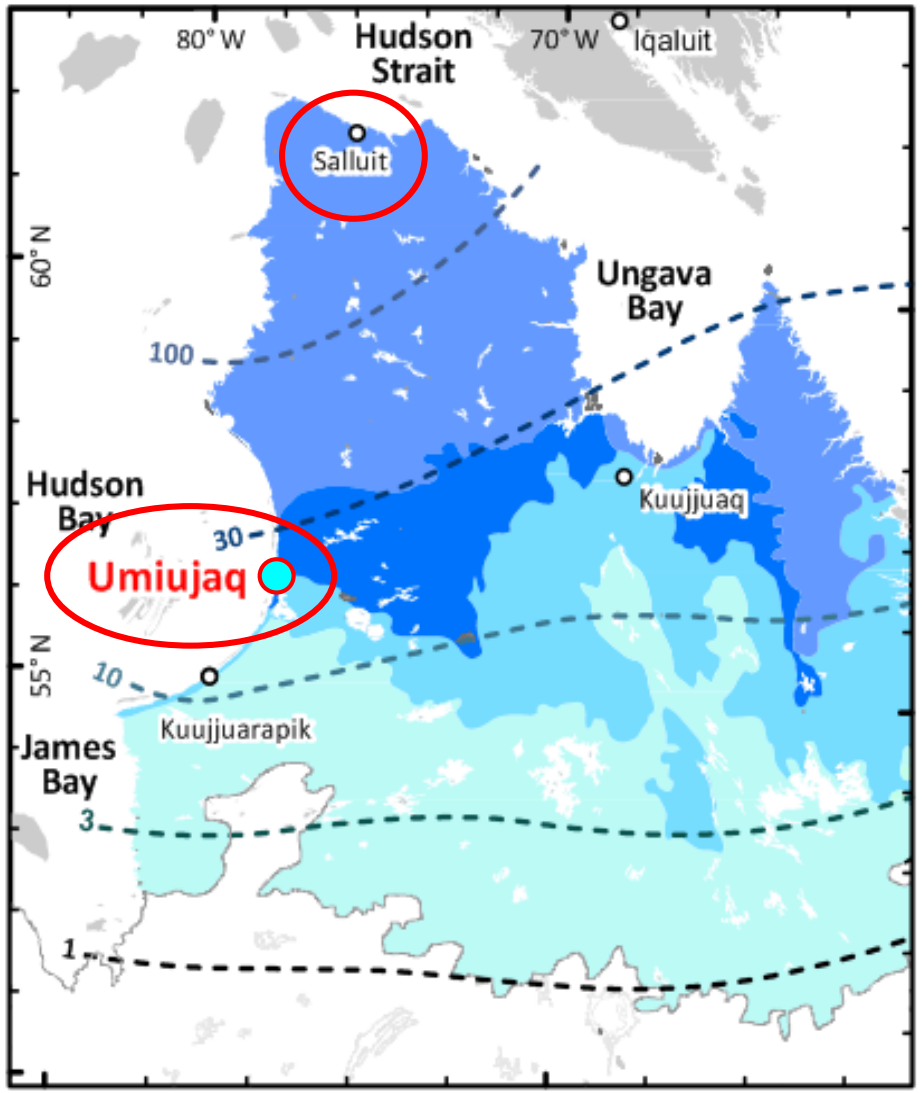


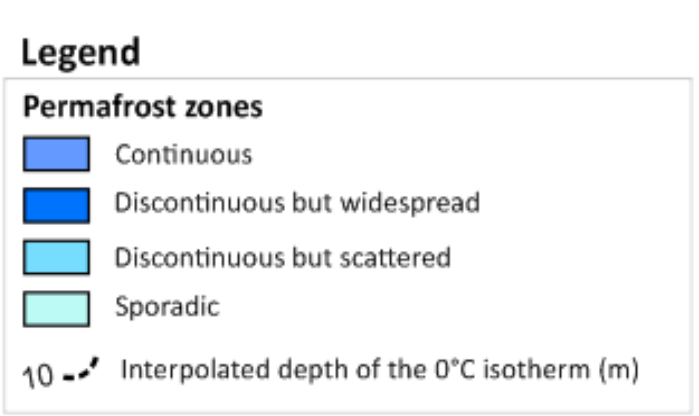


Future developments:

- Ion exclusion and cryo-suction

Study Sites / Data Collection : Umiujaq & Salluit Nunavik, Québec, Canada

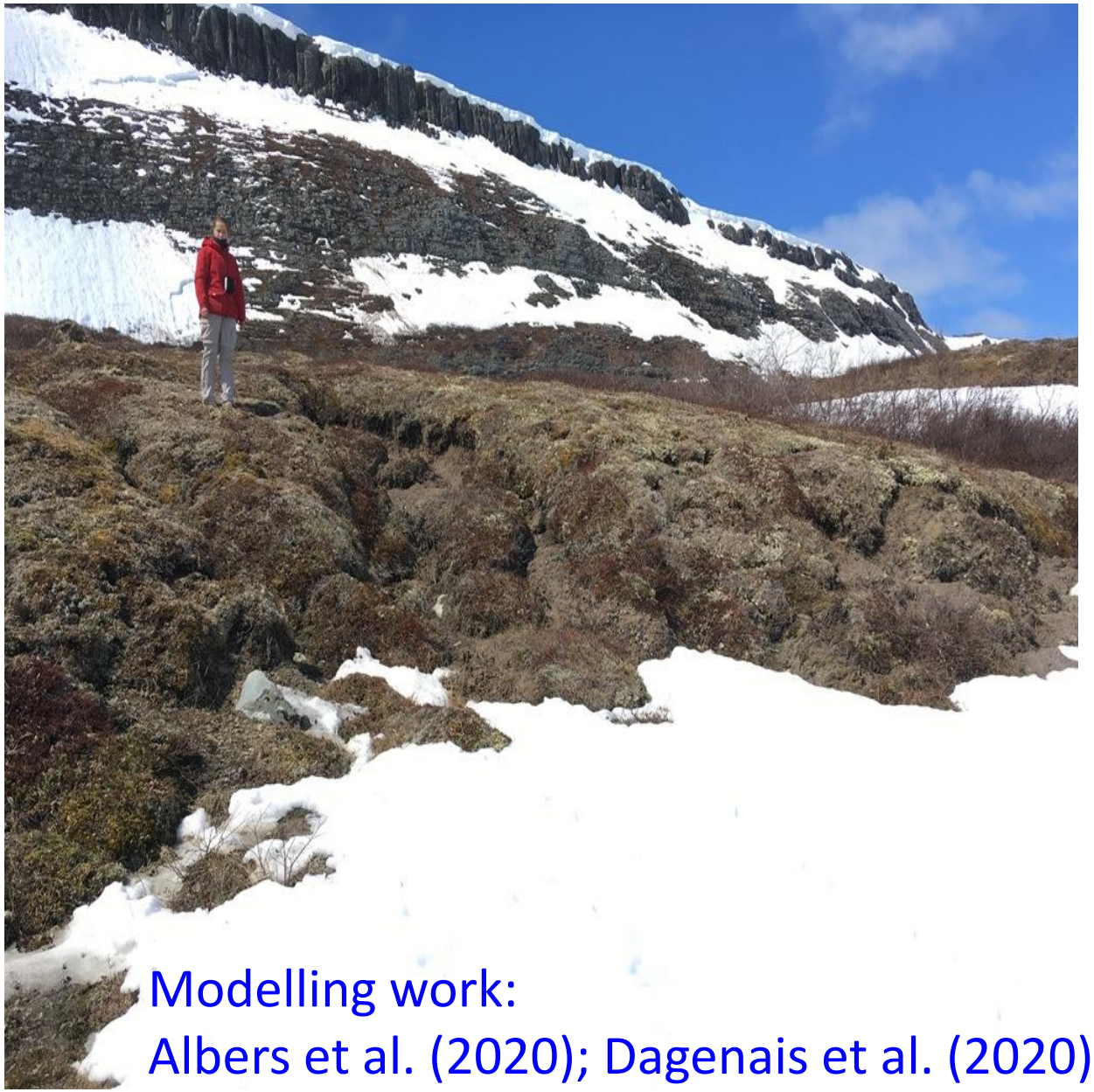




Context:

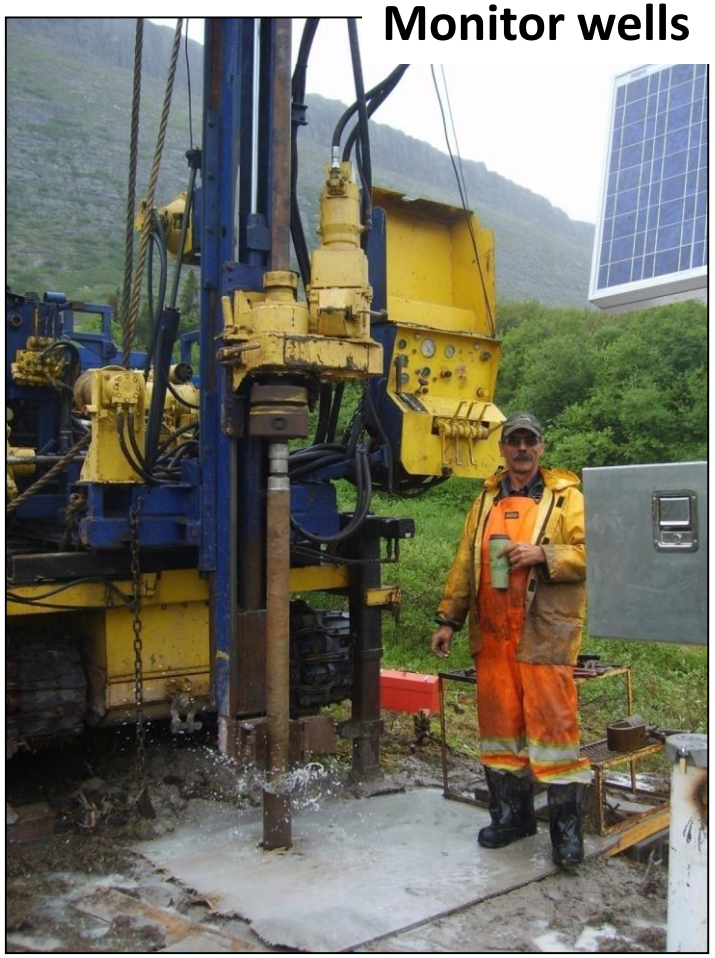
- Discontinuous & continuous permafrost
- Groundwater flow component
- Climate change, water supply
- Instrumentation / data collection

Umiujaq (Tasiapik Valley): Discontinuous permafrost zone

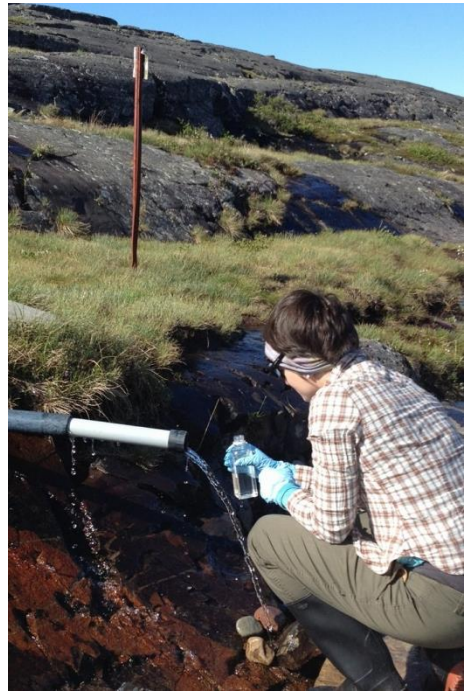


Modelling work:
Albers et al. (2020); Dagenais et al. (2020)

Monitor wells



Sampling

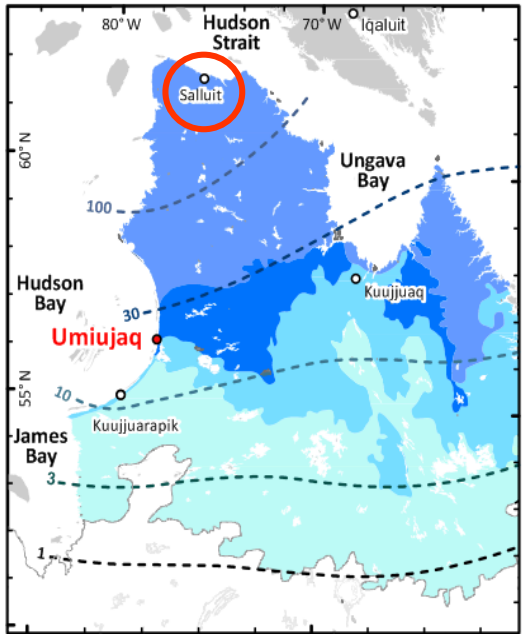


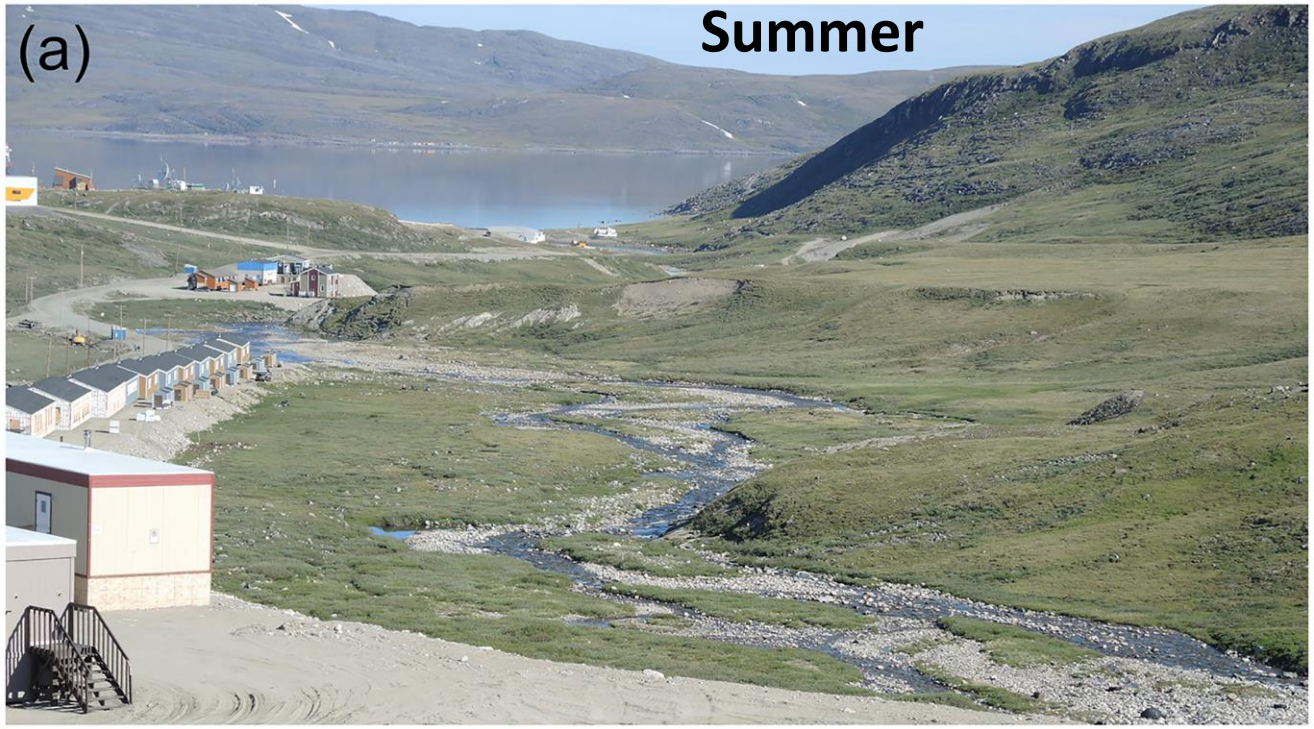
Gauging station

Lemieux et al (2020)
Fortier et al (2020)

Salluit

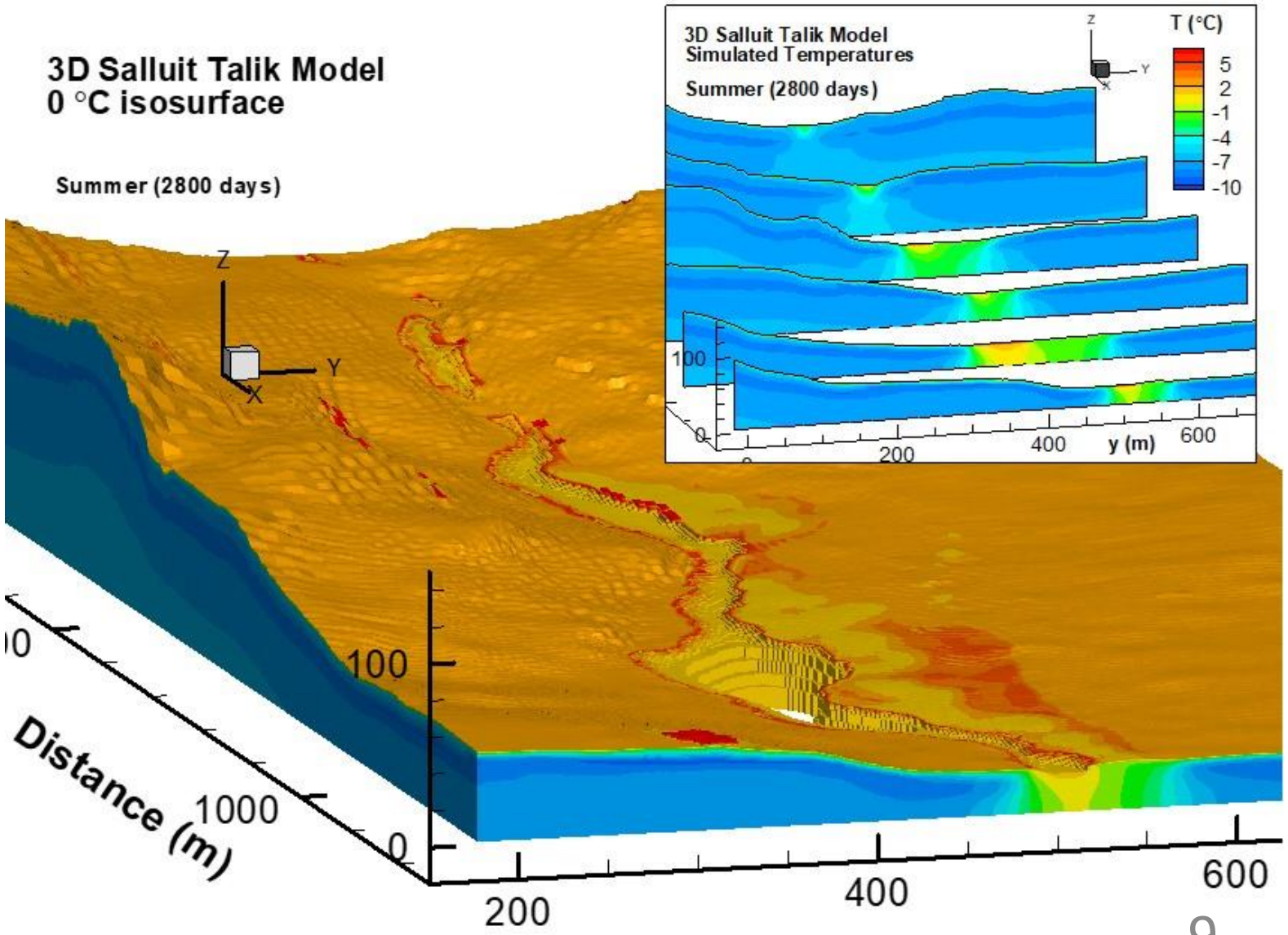
- Continuous permafrost
- River talik
- Icing events





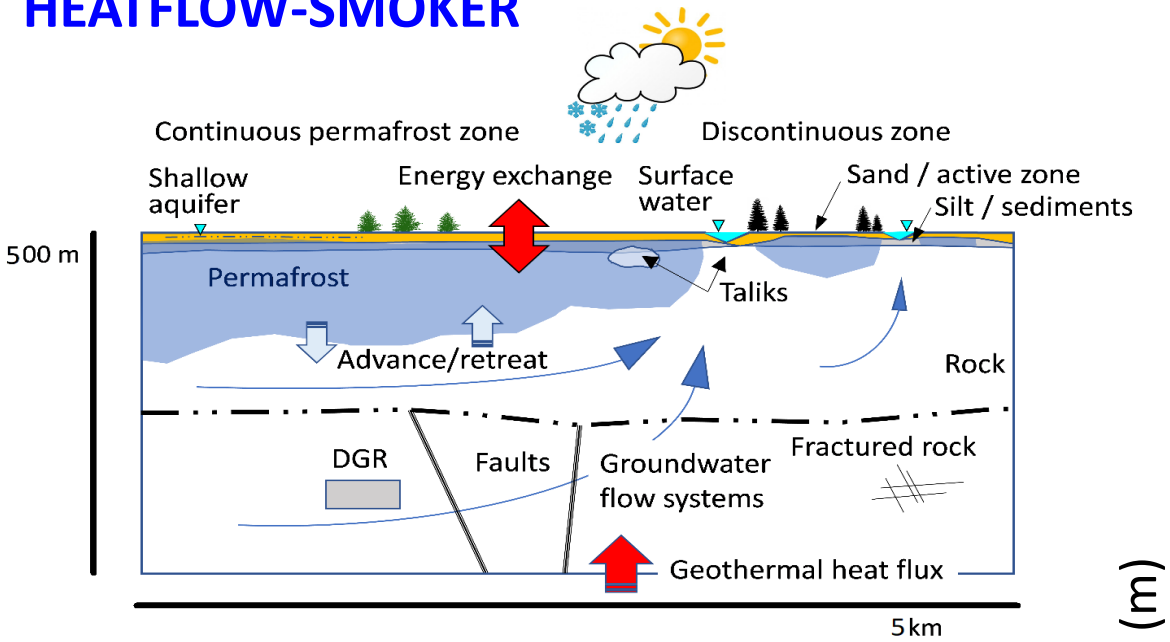
Salluit : 3D Numerical Simulation of a River Talik

Heatflow/Smoker model
(Liu et al. WRR; 2022)

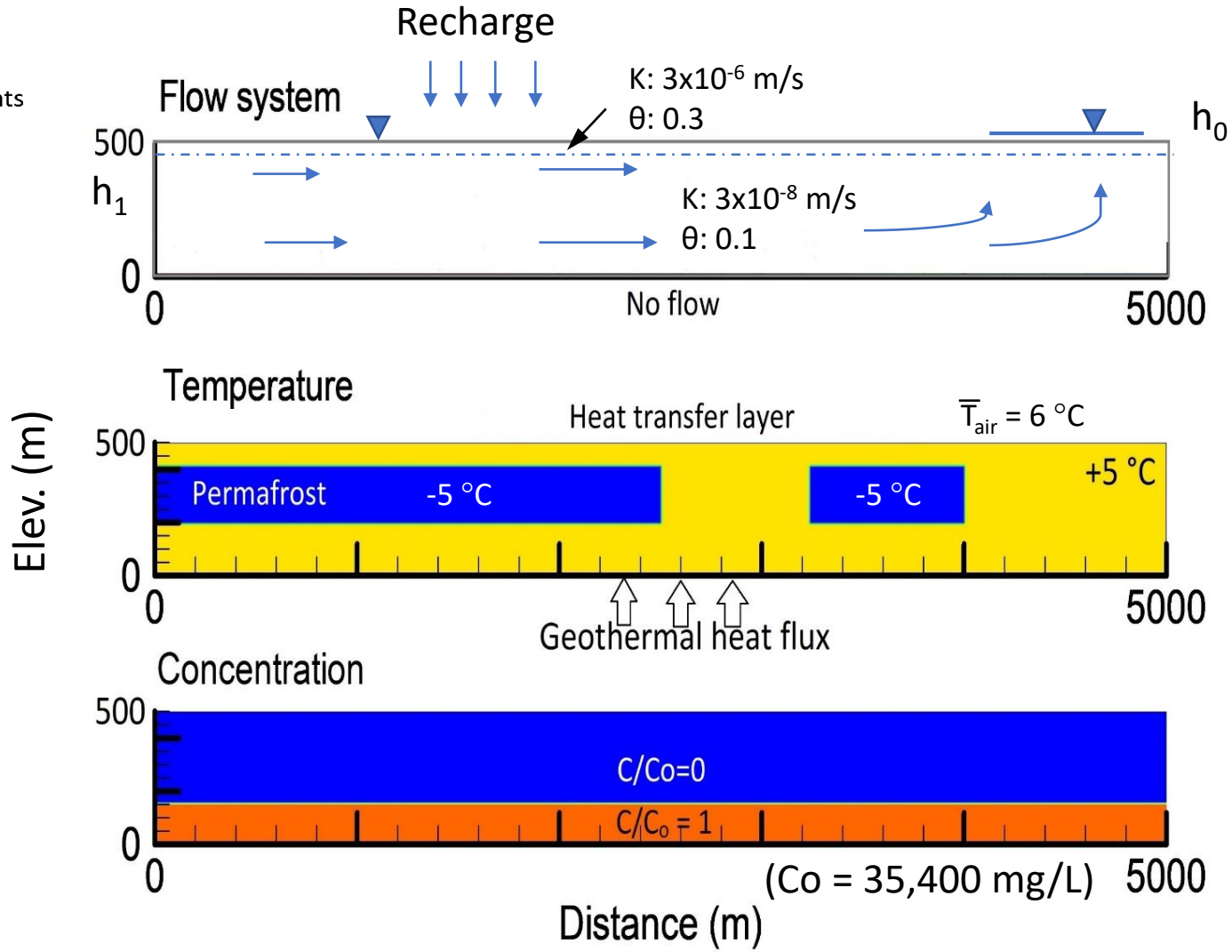


Conceptual model simulation:

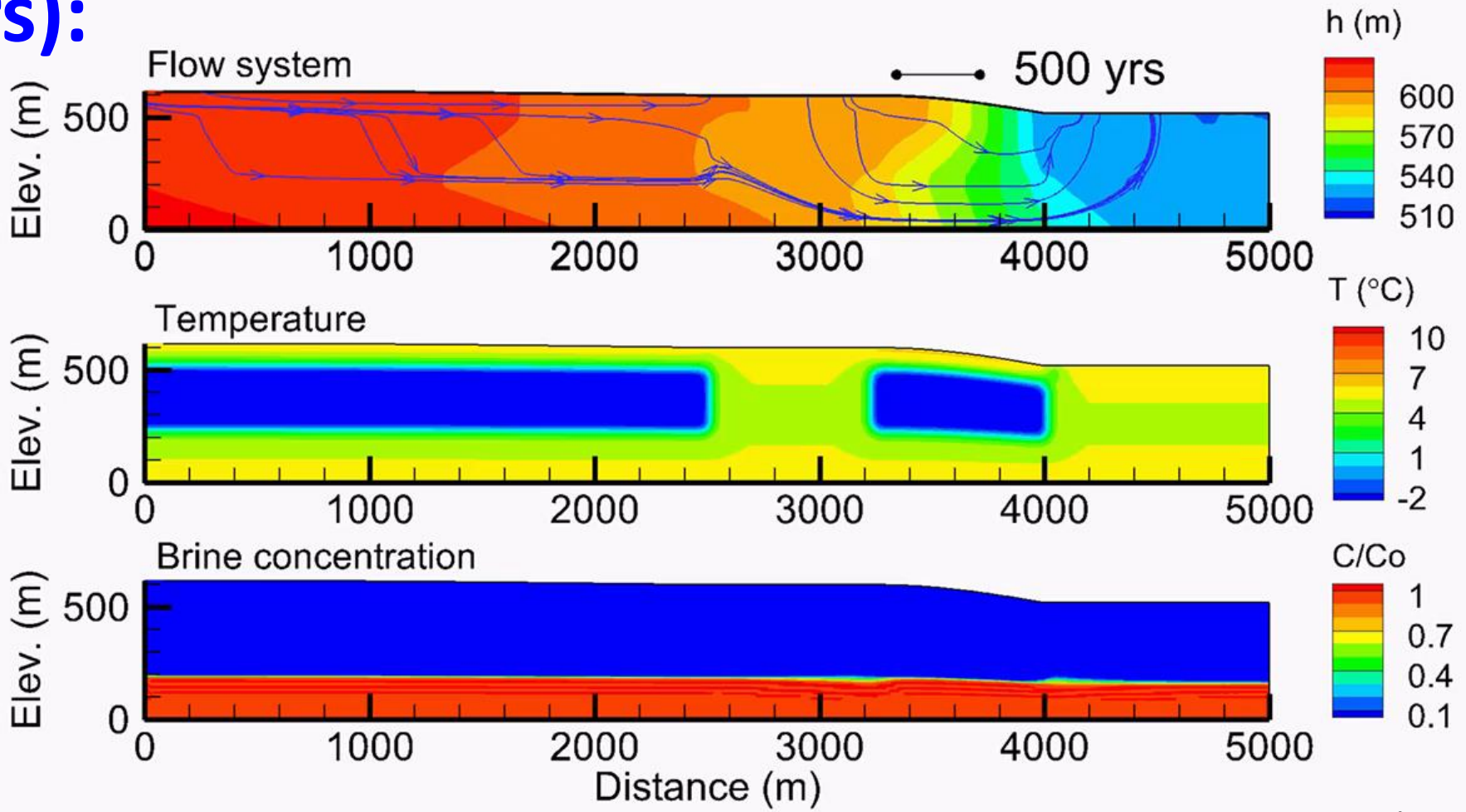
HEATFLOW-SMOKER



- 2D conceptual model
- 5000 m x 500 m
- Two permafrost blocks (200 m thick)
- Fully-saturated system
- Density-dependent flow ρ(T,C)
- Advective-conductive heat transport
- Advective-dispersive salt transport



Conceptual Simulation (0-4000 yrs):

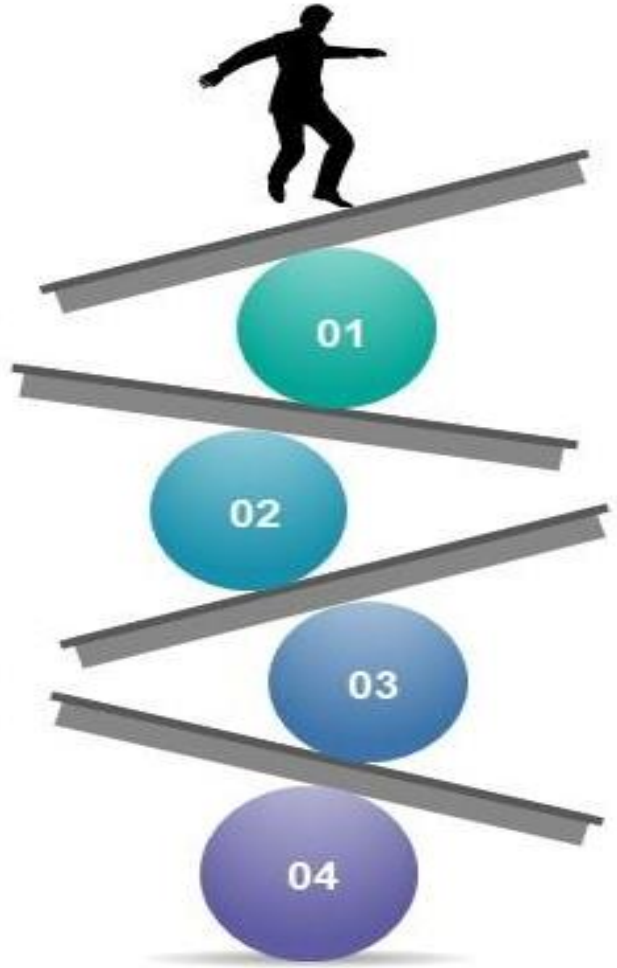


(Co = 35,400 mg/L)

27.3973 yrs

Anticipated challenges:

- Numerical challenges
- Climate change scenarios
- Realistic parameters
- Scale issues (space & time)



→ PhD: 4 year estimated time period (2022-2025)

Funding/Collaboration/Support

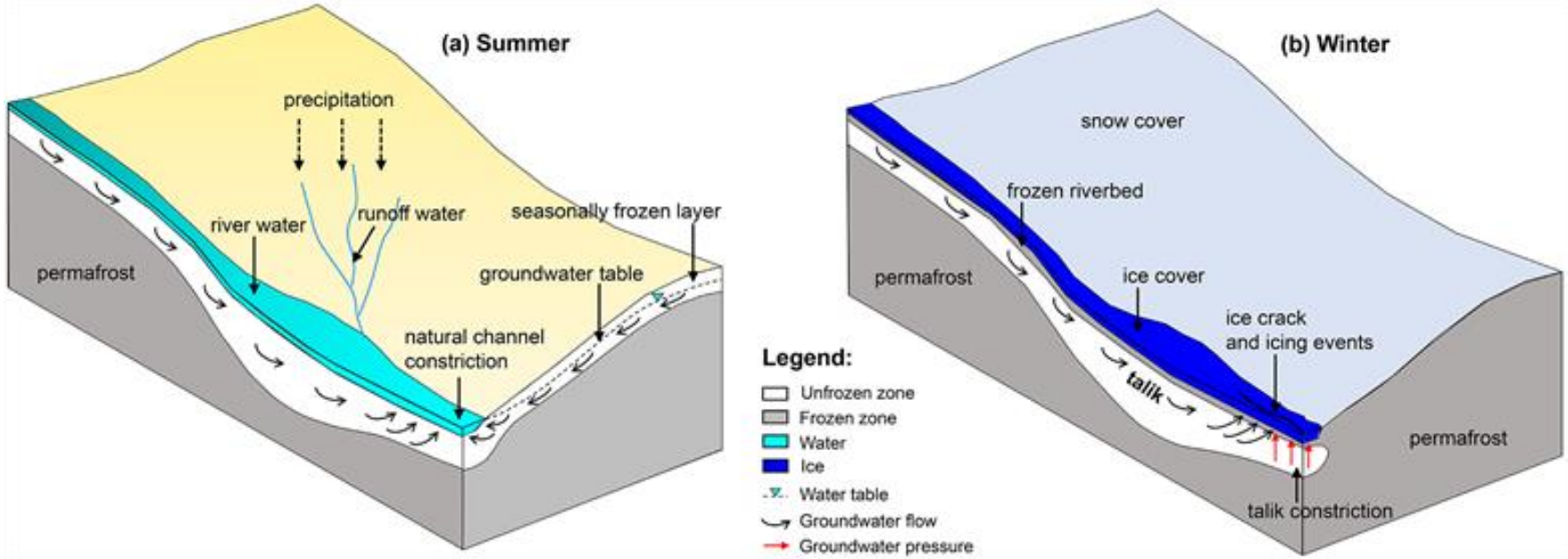
Future insight:

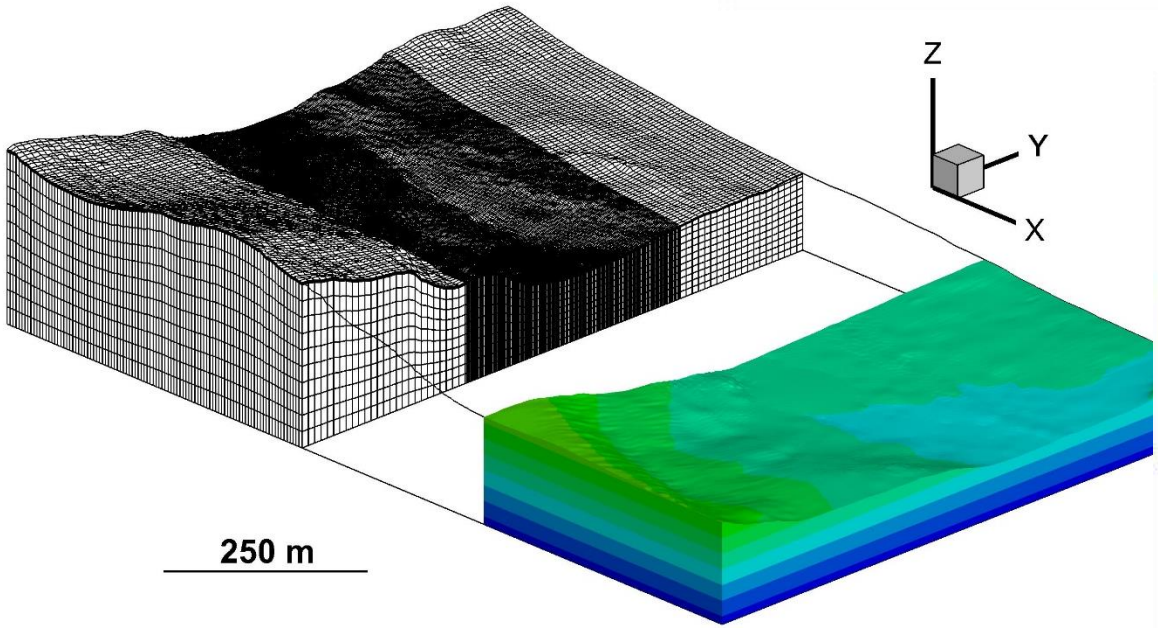
- Climate change
- DGR heating loads and migration pathways
- Groundwater flow, permafrost freeze/thaw and mass transport in discretely-fractured rock
- New processes (cryo-suction, ion-exclusion)
- Model benchmarking

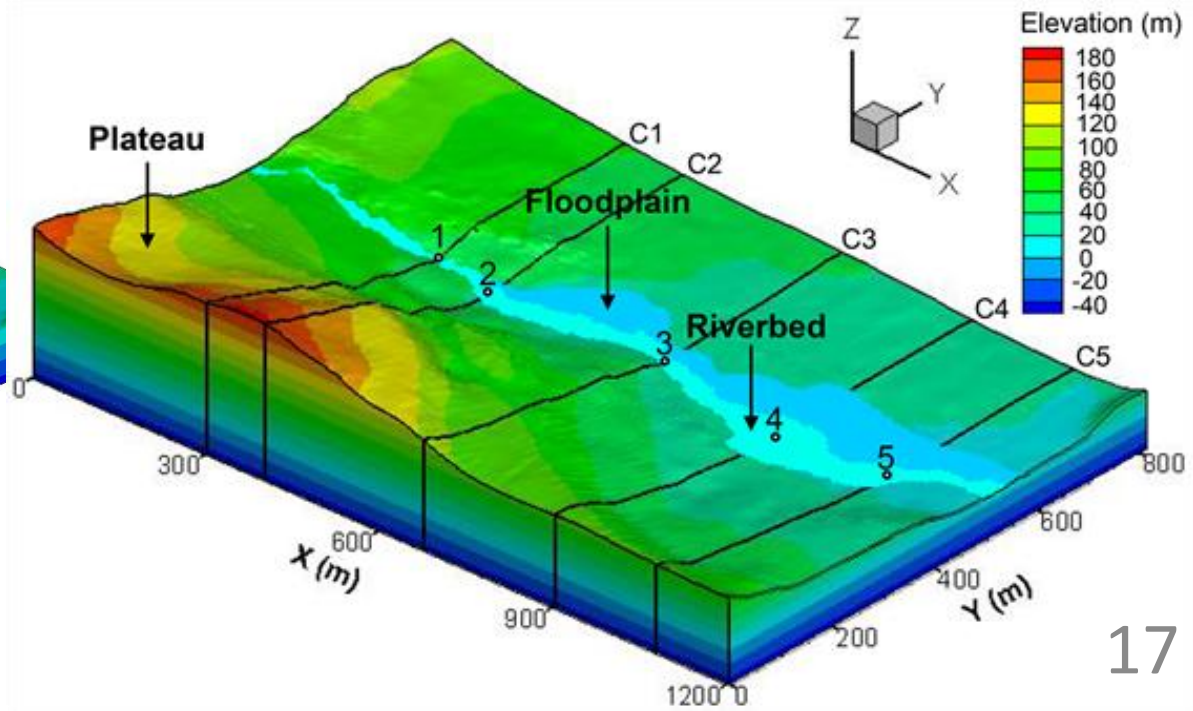
Research Summary

1. Interpret existing data at research sites (Umiujaq, Salluit).
   - Water levels, fluid/heat fluxes, settlement, permafrost thaw signatures
2. Numerical simulation models
   - New processes (cryo-suction, ion-exclusion, heave/settlement etc.)
   - Model testing, benchmarking
3. New insights:
   - Permafrost growth and decay within a single glacial cycle
   - Effects on groundwater flow systems & transport pathways
   - Multi-cycle scenarios on a time scale of up to one million years

Salluit : Conceptual and Numerical Model

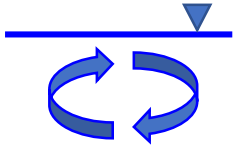




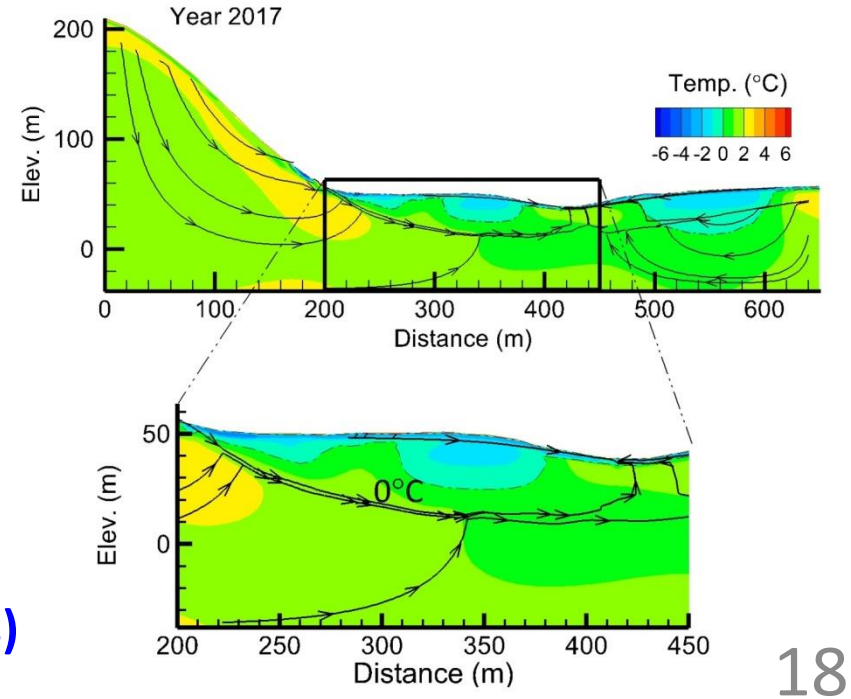


Take-Home Points:

- **Groundwater flow can contribute to permafrost thaw**
  … at surface and base of permafrost
- **Most sensitive to surface and near-surface properties, with positive feedback**

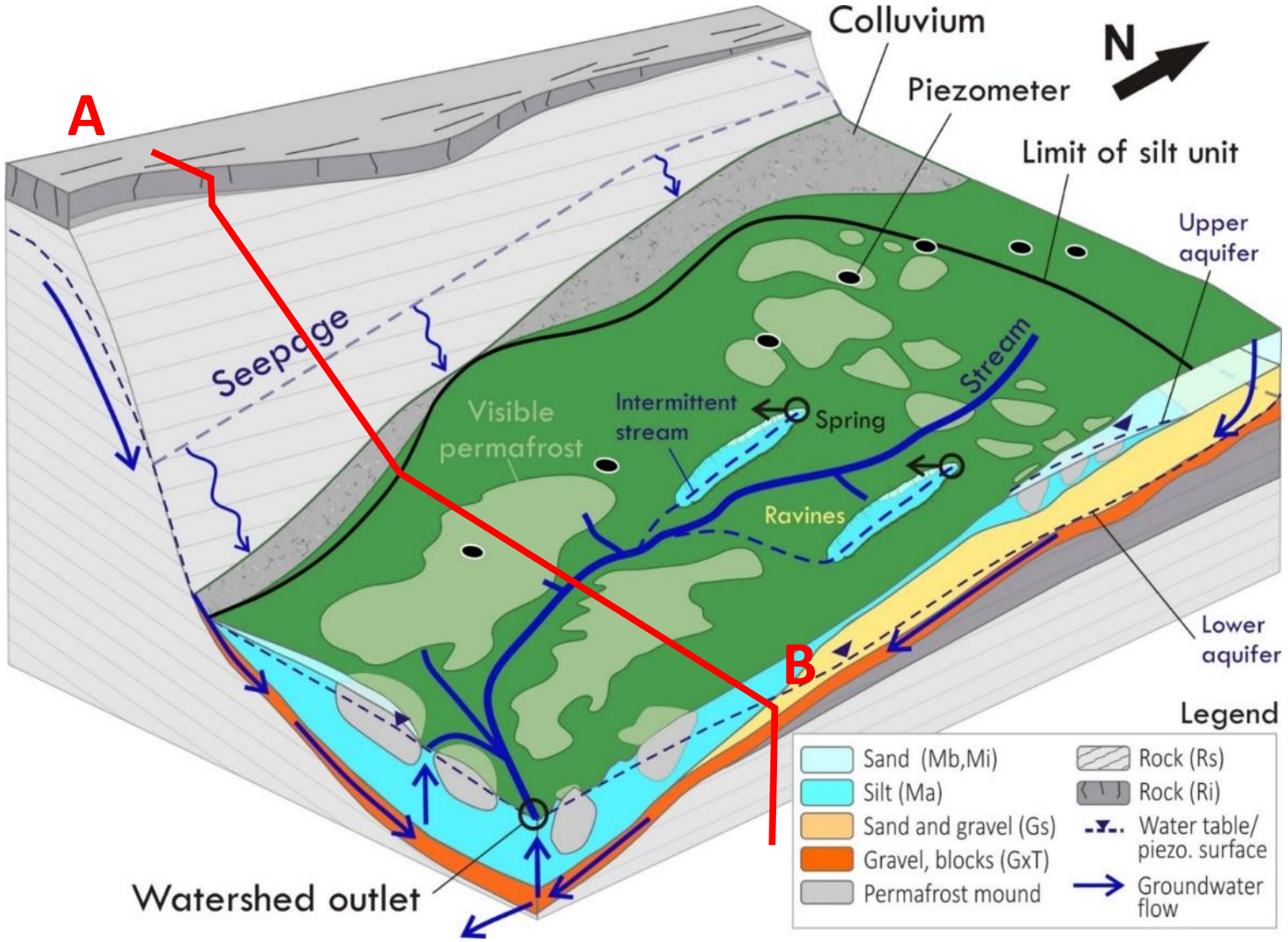


- **Groundwater flow :**
  - warmer recharge zones
  - colder discharge zones
- **Impact of flow through taliks**
  - icings, source of drinking water



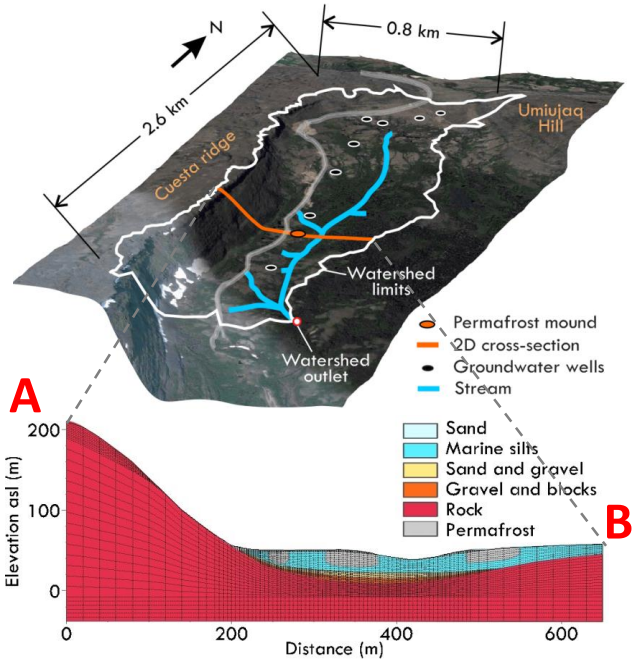
Hydrogeology Journal : Topical Collection 2020
Permafrost & Periglacial Processes (2020, in press)

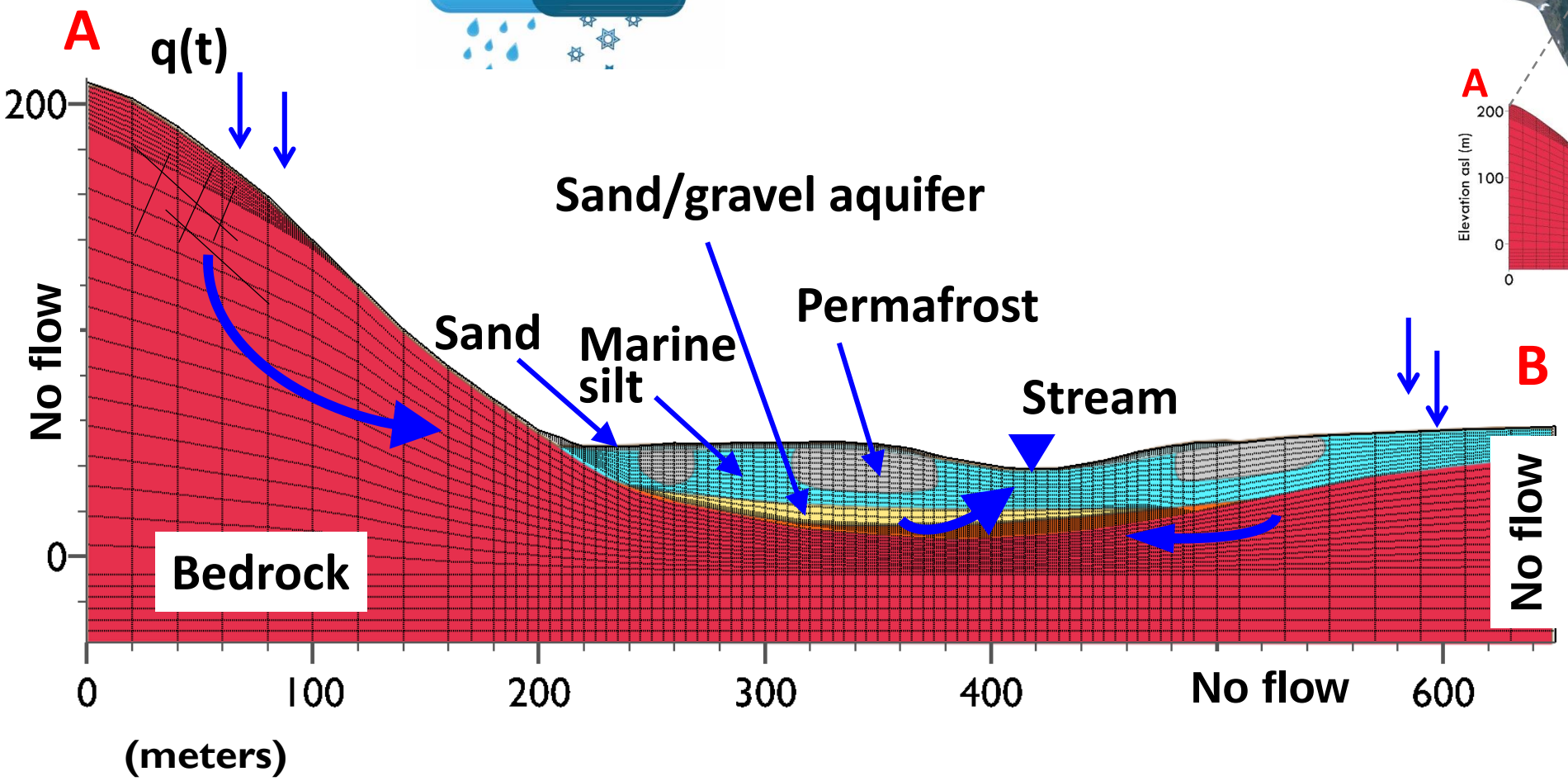
Numerical Modelling Approaches



2D Cryo-hydrogeological Numerical Model

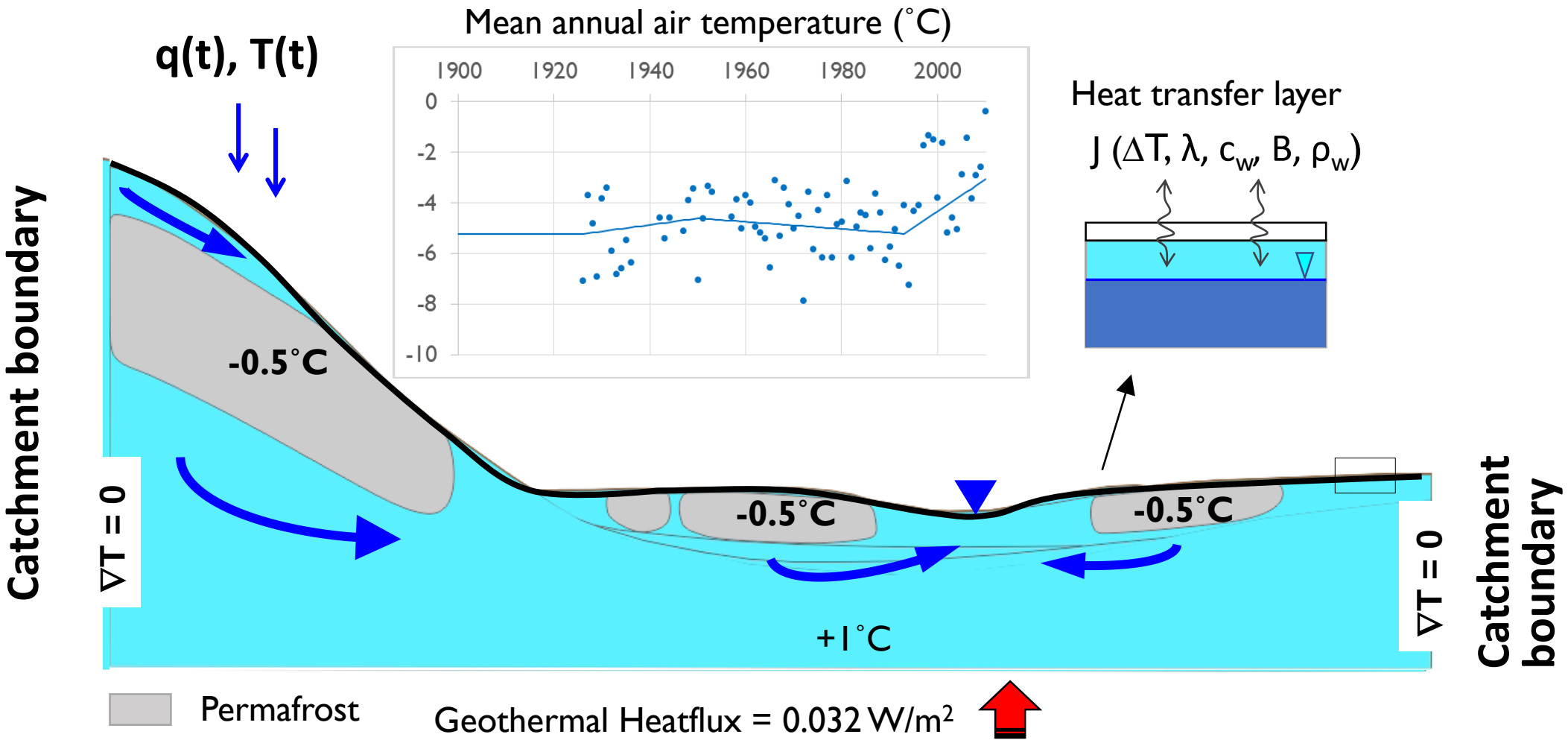
(Dagenais et al, 2020)

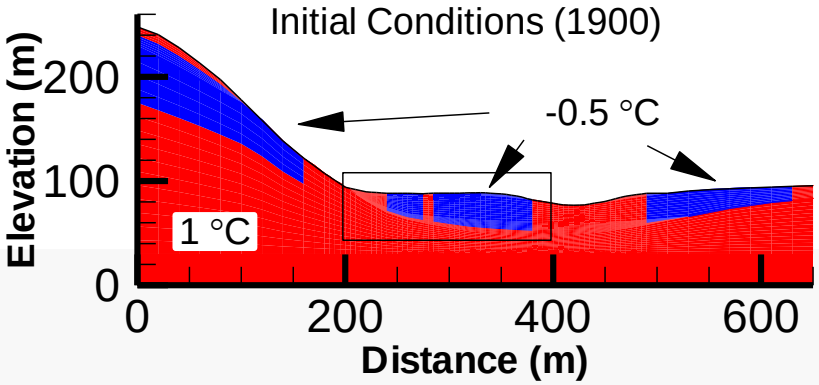


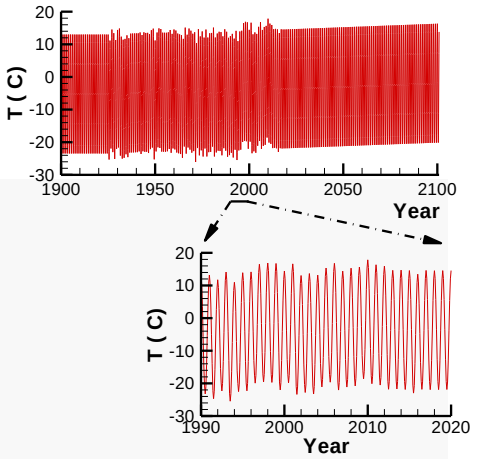


Umiujaq Model – Heat transfer

Boundary conditions and initial conditions (1900)



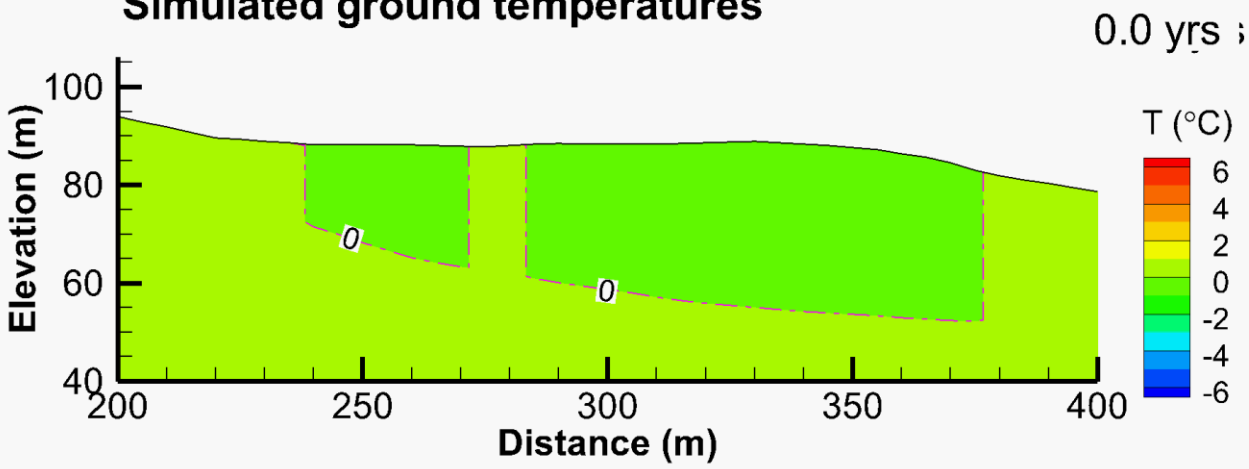




1900 – 2050 AD

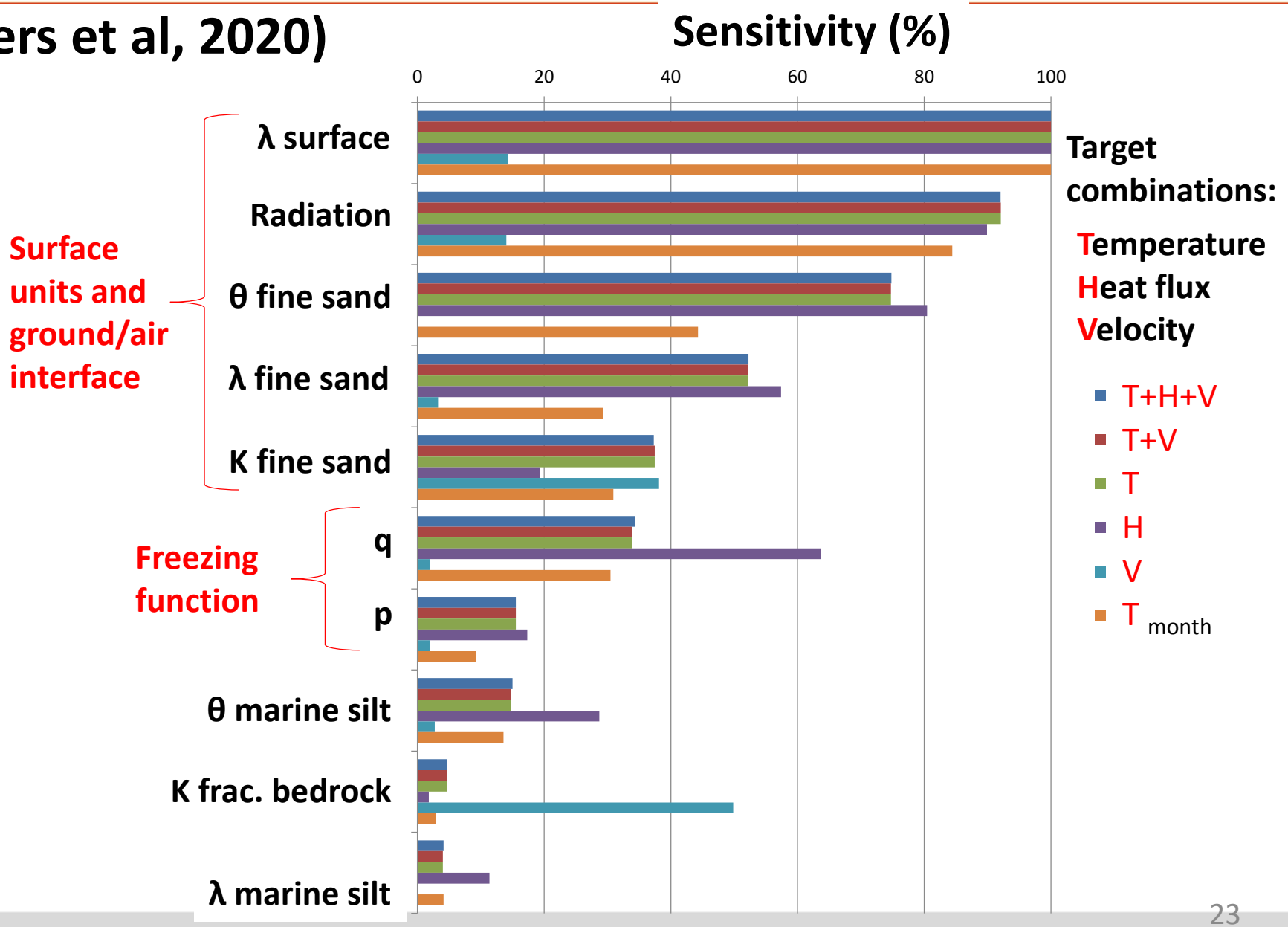
0 – 150 yrs

Umiujaq Model
Simulated ground temperatures



Parameter Sensitivity (PEST)

(Albers et al, 2020)

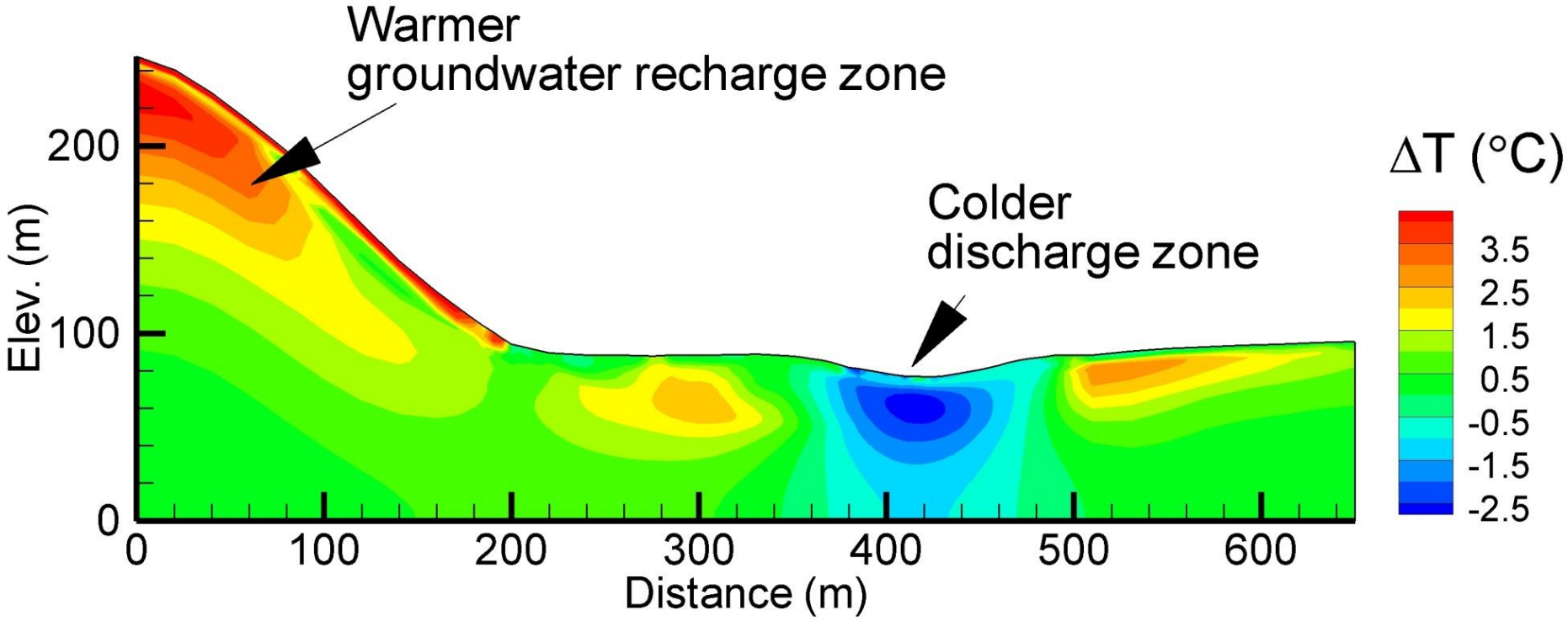


Effect of Advective Thermal Transport over Conduction

Umiujaq simulation:

Temperature change when groundwater flow is included

2017



Heatflow/Smoker

(Molson & Frind, 2020)

Coupled processes : Groundwater flow, heat transfer, freeze/thaw

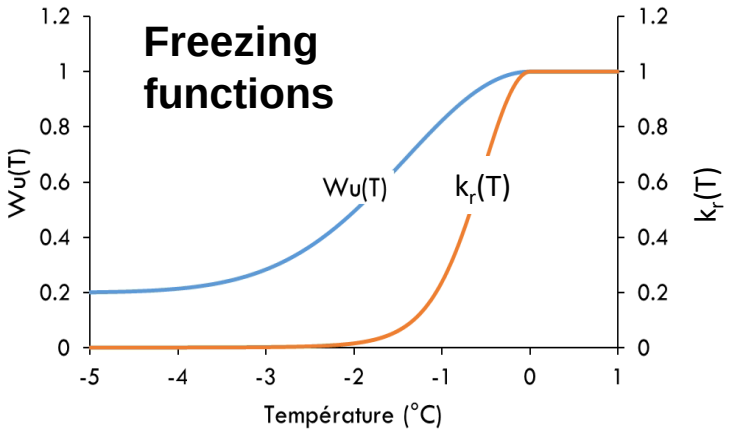
Groundwater Flow: (head ψ)

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

Heat Transport (temperature T):

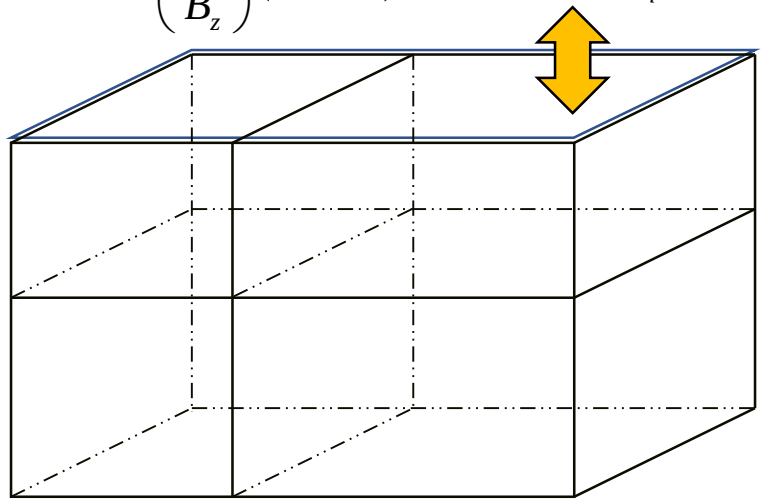
$$-\frac{\partial}{\partial x_i}\left(\theta S_w c_w \rho_w v_i T\right)+\frac{\partial}{\partial x_i}\left(\bar{\lambda}(T)+\theta S_w c_w \rho_w D\right)\frac{\partial T}{\partial x_j}+\Omega=\frac{\partial\left(C_o T\right)}{\partial t}$$

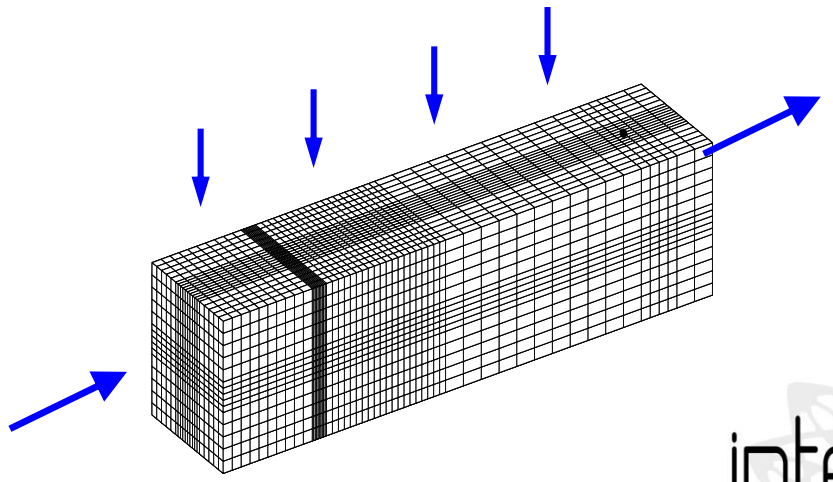
$$C_o=\theta S_w c_w \rho_w+\theta S_i c_i \rho_i+(1-\theta)c_s\rho_s+\theta\rho_i L\left(\frac{\partial S_w}{\partial T}\right)$$



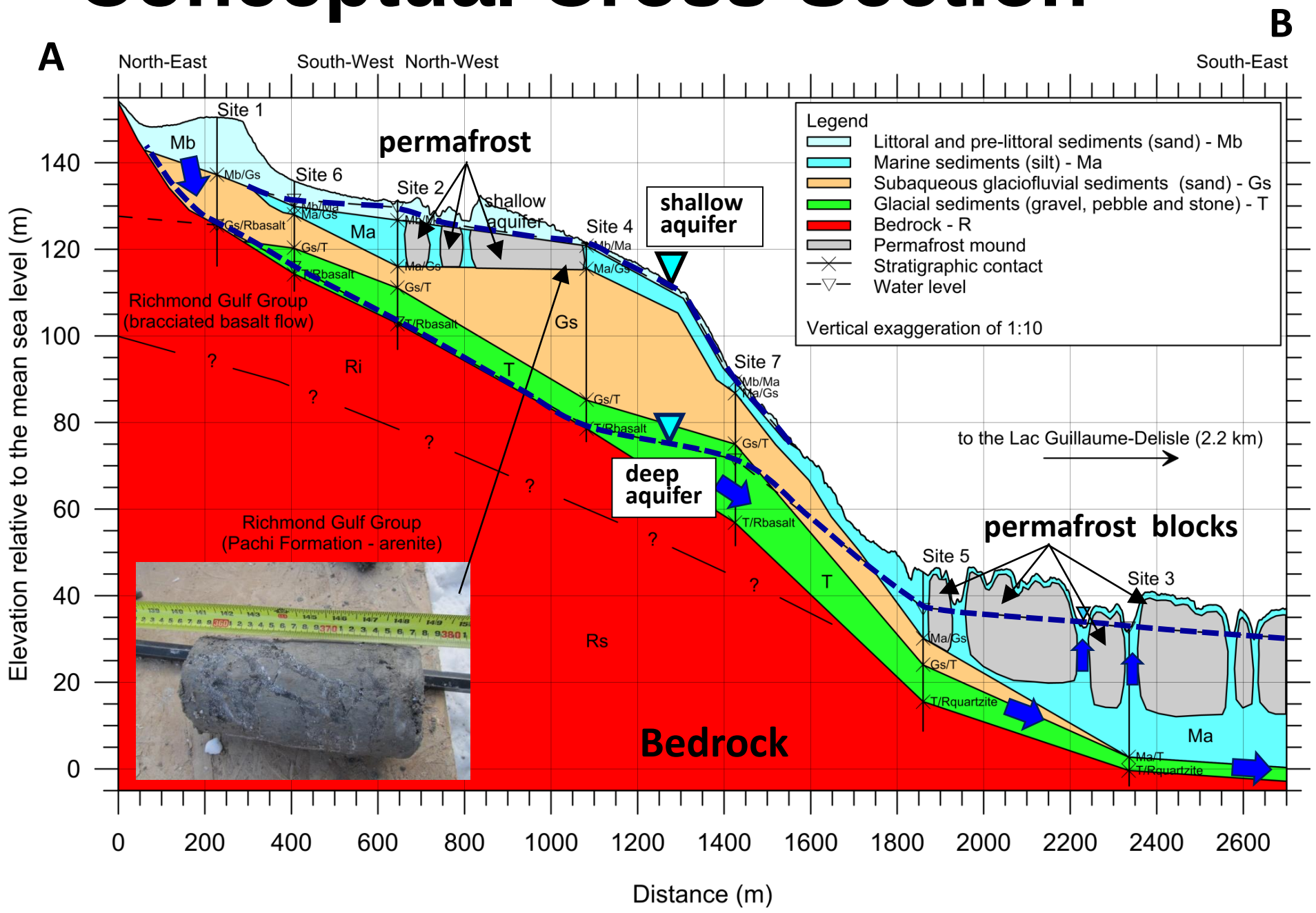
Air-Ground
Thermal Boundary Condition

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





Conceptual Cross-Section



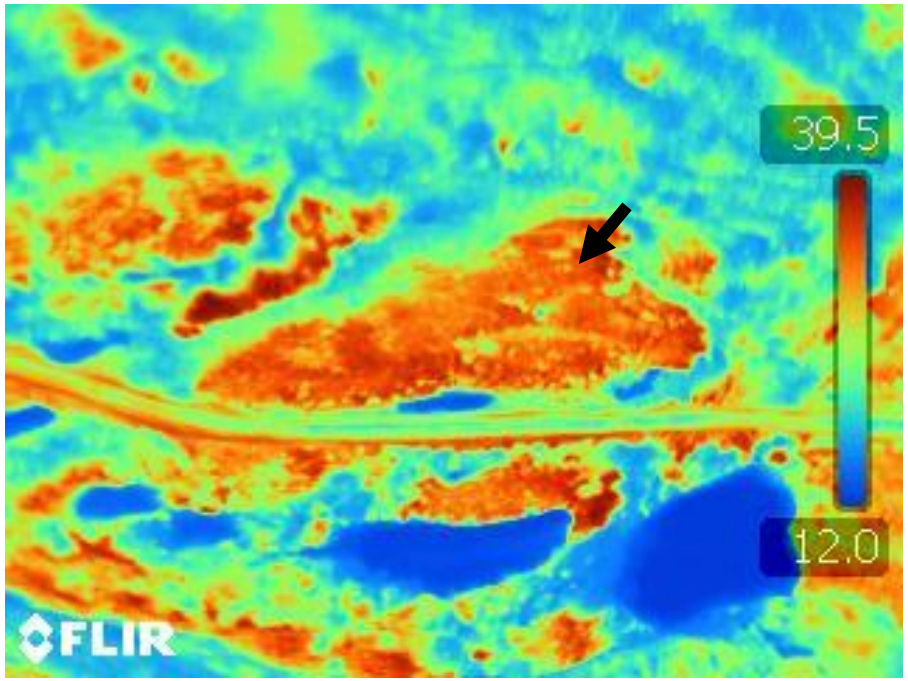
Résultats

Prise d'images infrarouges:

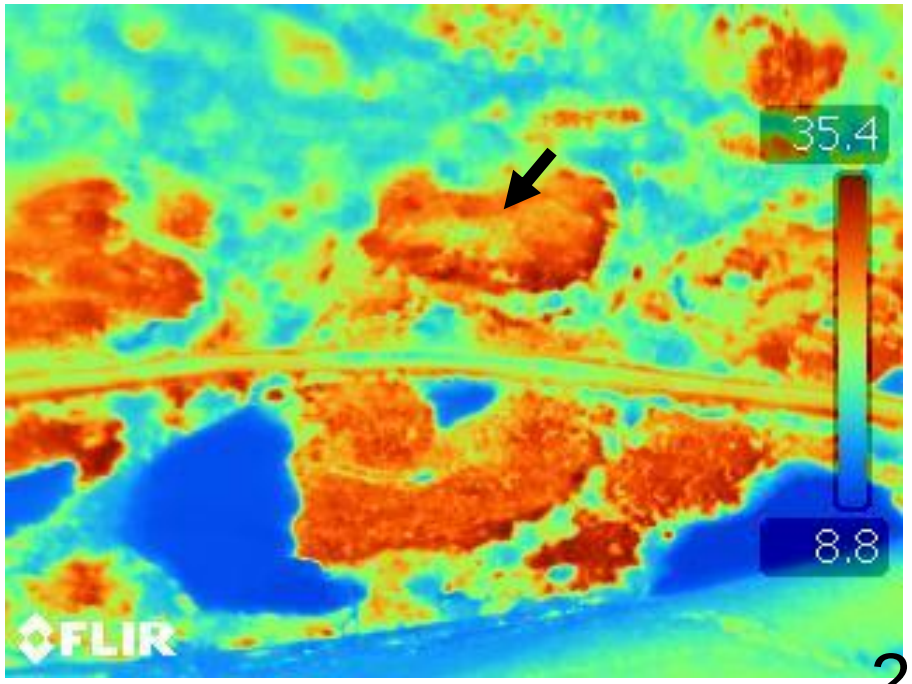
- Déterminer la variation spatiale des températures de surface
- Déterminer l'emplacement des sondes HOBO

Domaine visible: Buttes à Anne-Marie Leblanc et Sylvie Buteau

Journée ensoleillée 2019-07-09: Tair = 13.5°C



Domaine infrarouge: Butte à Anne-Marie Leblanc



Domaine infrarouge: Butte à Sylvie Buteau

Field-scale simulations and scenario testing

- Scenarios of climate change, deep permafrost growth and decay
- Flow system behaviour – feedback : recharge/discharge zones of local, intermediate and deep regional flow systems, dynamic permafrost evolution, including taliks.
- Scenarios of DGR heating loads, and hydro-thermal properties of crystalline and sedimentary rock regimes
- Freeze/thaw and mass transport in discretely-fractured rock.
- Transport pathways from a DGR under permafrost growth and thaw cycles.
- Time scales, groundwater age evolution under changing permafrost depths