Demonstration of the ACE (Arctic Coastal Erosion) model at Drew Point, AK during a permafrost bluff block collapse event in summer 2018

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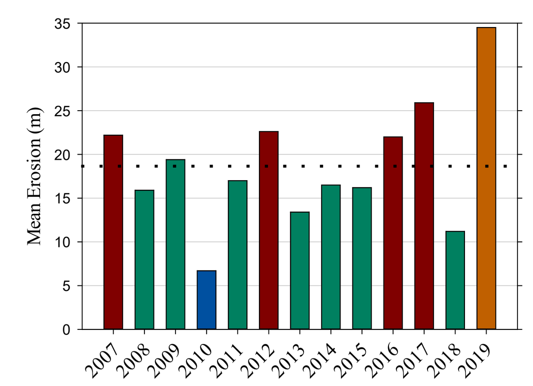
Motivation

The Arctic is warming at **2-3 times** the rate of the rest of the U.S. resulting in **accelerated rates of coastal erosion!**

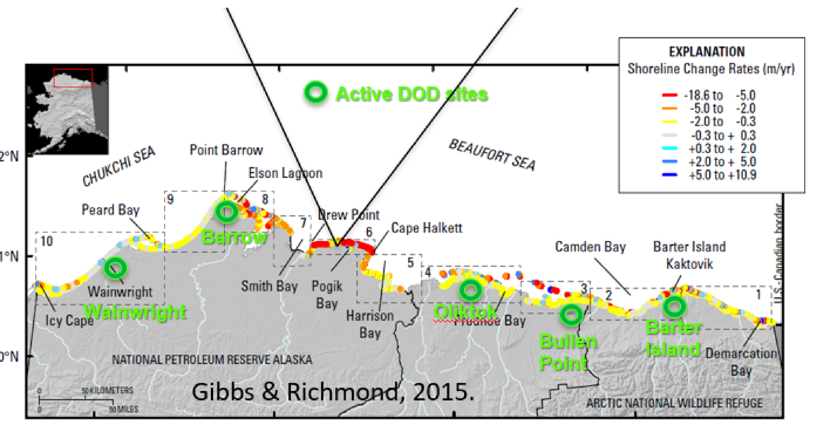
- Primary culprit is **loss of Arctic sea ice**: since 1979 sea ice has lost 51% in area and 75% in volume
  - Increasing **ice-free season**
  - Increasing **wave energy** and **storm surge**
  - Increasing **sea water** temperatures



Certain locations lost ~200 m (~2 football fields in length) b/w 2007-2017!

Erosion is threatening:

- **Coastal communities**: threatened with displacement
- **Coastal infrastructure**: active DoD sites, including toxic waste sites, in northern Alaska
- **Global carbon balance**: permafrost stores greenhouse gases (CO_2, CH_4, NO_2).



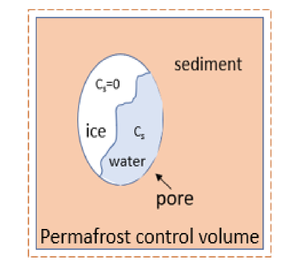
A demonstration of the ACE Model is presented here for a portion of the summer 2018 conditions at Drew Point, AK, during which a block collapse event was documented with thermistor data and time-lapse photography. We demonstrate that the ACE Model is capable of reproducing the observed erosion behavior, including niche formation/geometry, thermal denudation, and block collapse timing. This model can be used to rigorously investigate erosion drivers and how climate change will influence future erosion behavior at Drew Point, as well as typological assessment of erosion along the North Slope of Alaska to enable estimates of shoreline change at the coarse scale of Earth system models.

Thermal Model

- ***Transient heat conduction*** in a non-homogeneous porous media with water-ice phase change:

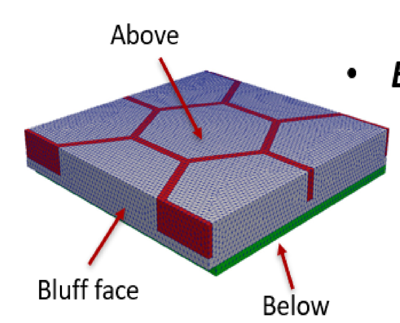
$$(\widetilde{\rho c_p} + \widetilde{\Theta})\frac{\partial T}{\partial t} = \nabla \cdot (\boldsymbol{K} \cdot \nabla T)$$

where $\widetilde{\Theta} \coloneqq \rho_f L_f \frac{\partial f}{\partial T}$ incorporates phase changes through soil freezing curve, $\frac{\partial f}{\partial T}$.

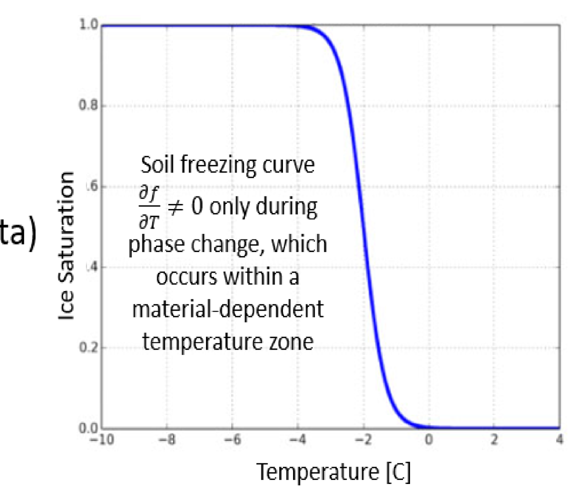


$\tilde{\rho}$: density from mixture model
$\widetilde{c_p}$: specific heat from mixture model
$\boldsymbol{K}$: thermal diffusivity tensor
ρ_f: ice density
L_f: latent heat of water-ice phase change
f: ice saturation ($\in [0,1]$)
$\frac{\partial f}{\partial T}$: soil freezing curve (depends on salinity)

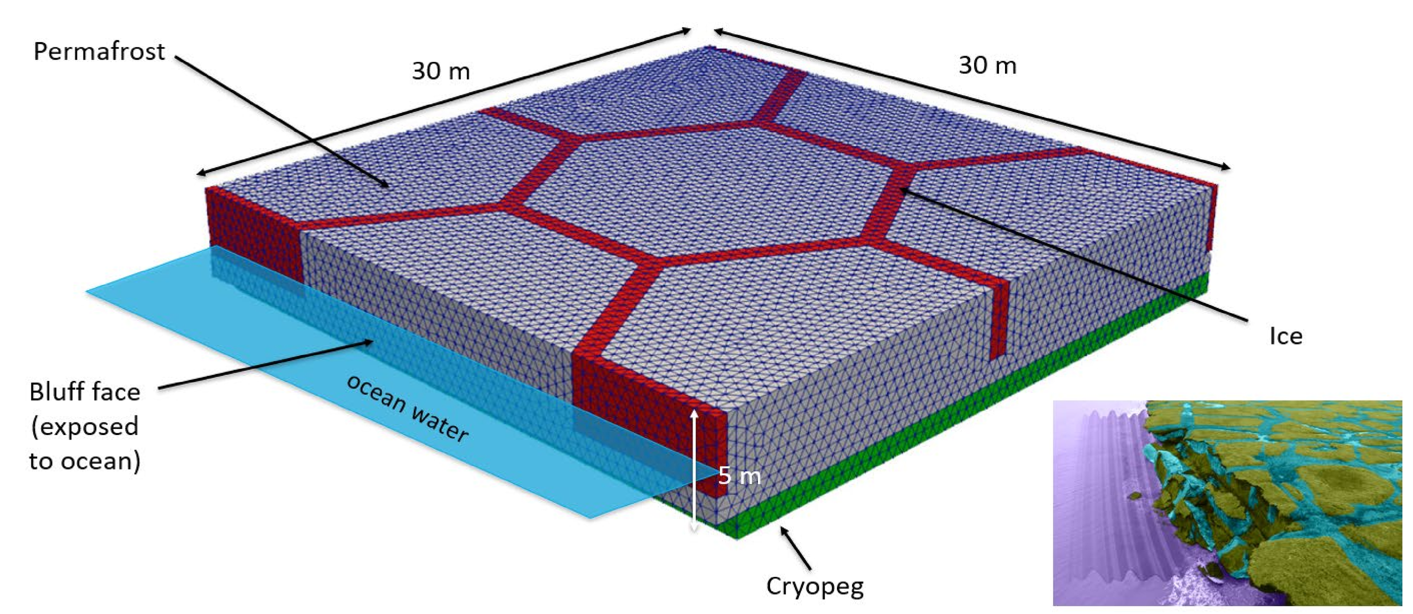
- Computes ***temperature*** T and ***ice saturation*** f (needed by mechanical model)



- ***Boundary conditions*** (from wave model/data)
  - Local geothermal heat flux from below
  - Mean annual air temp from above
  - Air/ocean temp at bluff face



Anatomy of a canonical computational domain



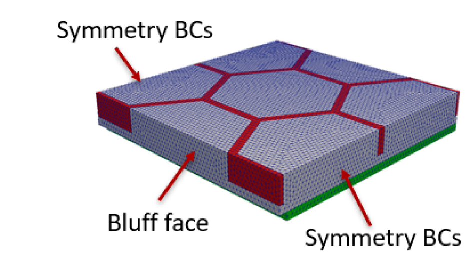
Mechanical Model

- Finite deformation ***time-dependent*** variational formulation for ***solid mechanics problem*** obtained by minimizing the energy functional:

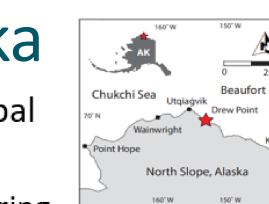
$$\Phi[\boldsymbol{\varphi}] \coloneqq \int_\Omega A(\boldsymbol{F}, \boldsymbol{Z})\, dV - \int_\Omega \rho \boldsymbol{B} \cdot \boldsymbol{\varphi}\, dV - \int_{\partial_T \Omega} \boldsymbol{T} \cdot \boldsymbol{\varphi}\, dS$$

$A(\boldsymbol{F}, \boldsymbol{Z})$: Helmholtz free-energy density
$\boldsymbol{Z}$: material variables
$\boldsymbol{F}$: deformation gradient ($\nabla \boldsymbol{\varphi}$)
ρ: density
$\boldsymbol{B}$: body force
$\boldsymbol{T}$: prescribed traction

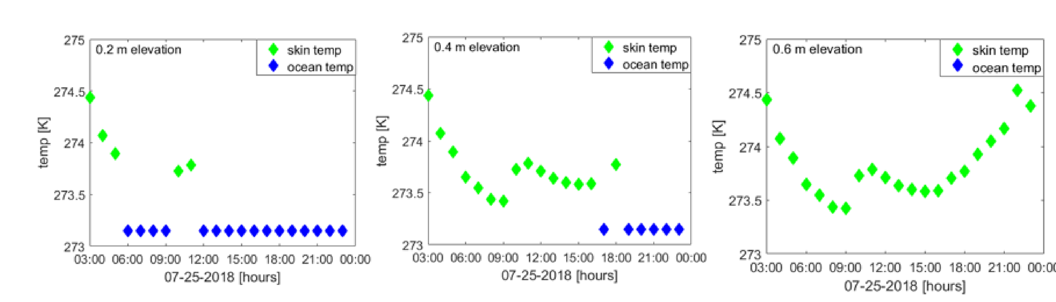
  - Computes ***displacements*** and ***new computational geometry*** (following erosion)
- ***J_2 plasticity*** extended to large-deformation regime ***constitutive model*** for **ice** and ***permafrost***
  - Incorporates all mechanisms that lead to deformation, plastic flow and creep of polycrystalline materials like ice
  - Minimal calibration parameters
  - Simplest material model with plastic behavior
  - Modified to be a function of ice saturation f and porosity
- ***Boundary conditions:***
  - ***Symmetry BCs*** on lateral sides
  - ***Wave pressure Neumann BC*** on bluff face (from wave model).



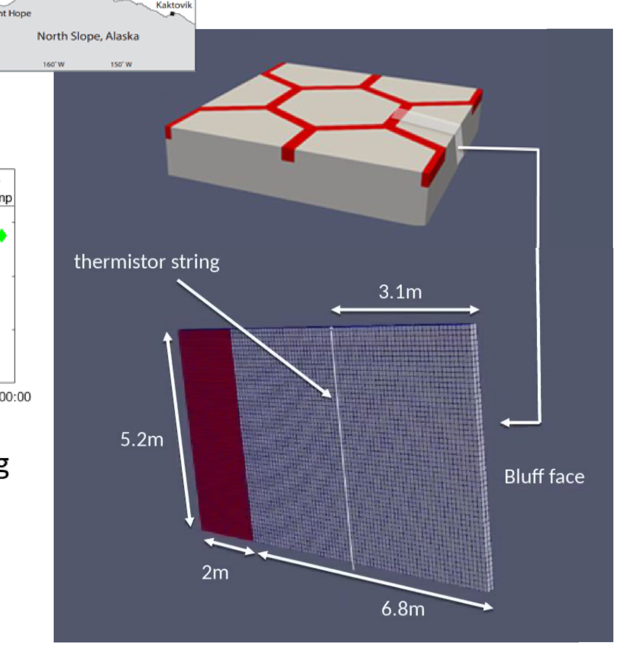
2.5D Slice at Drew Point, Alaska



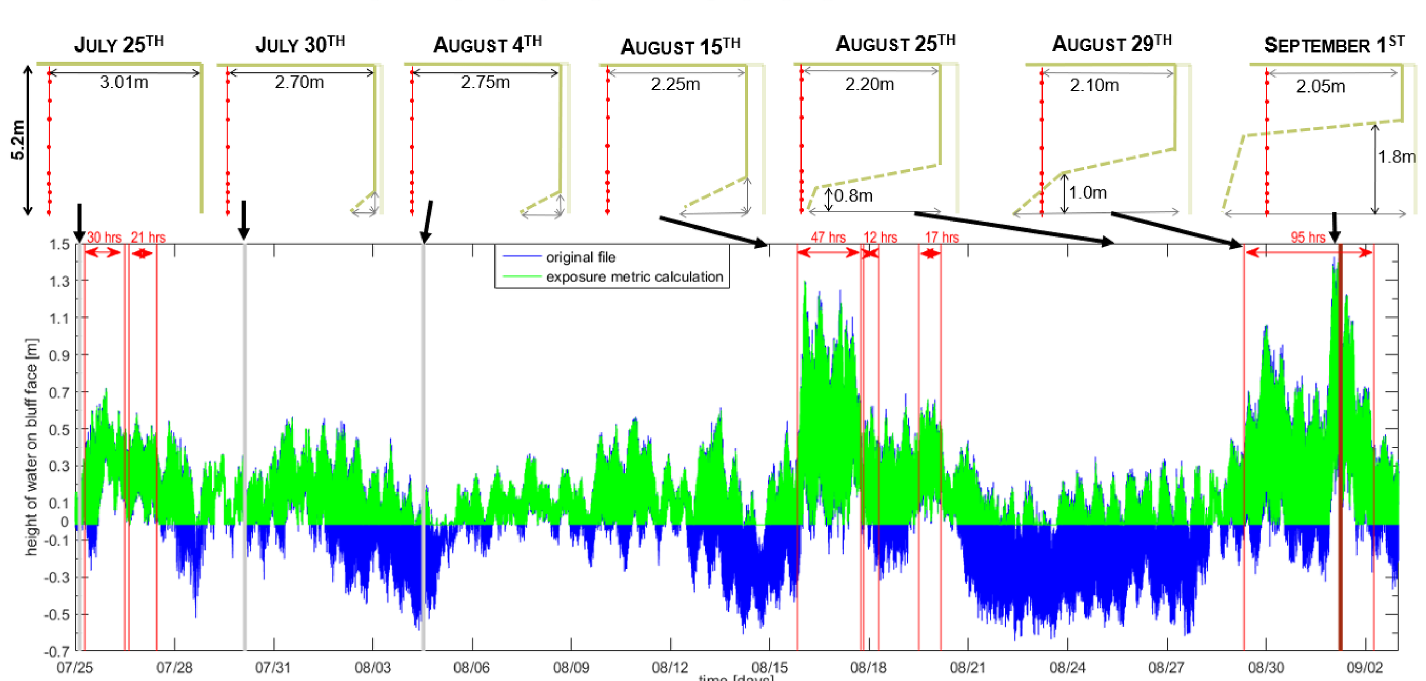
- Computational domain is ***2.5D cross-section*** of archetypal 3D bluff geometry discretized using a uniform hex grid.
  - Slice of permafrost is exposed to ***realistic BC data*** occurring at Drew Point, Alaska (example for July 25, 2018 below)



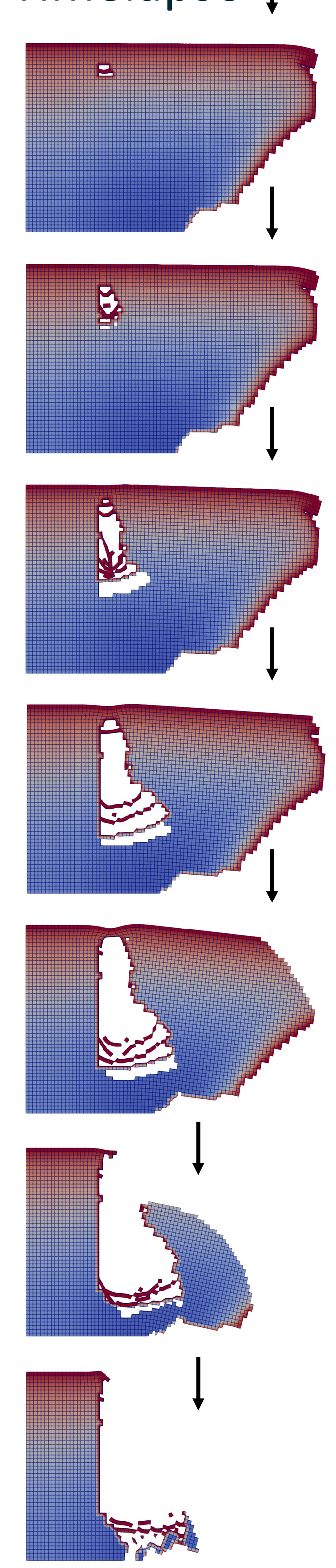
  - ***Initial temperature field*** obtained from vertical thermistor string placed into DP1-1 ice core at Drew Point.
- ***Material properties*** determined from laboratory experiments on frozen soil samples from Drew Point, Alaska
- ***Implicit*** Newmark for mechanical, ***explicit*** forward Euler for thermal (stable $\Delta t = 1$ hour)



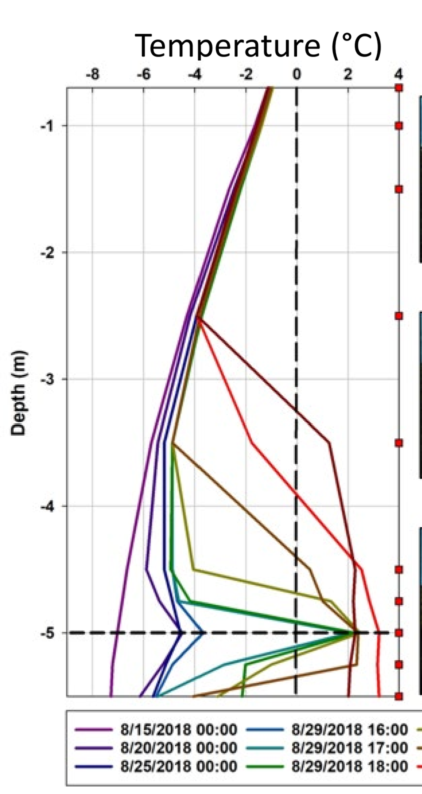
Validation Case

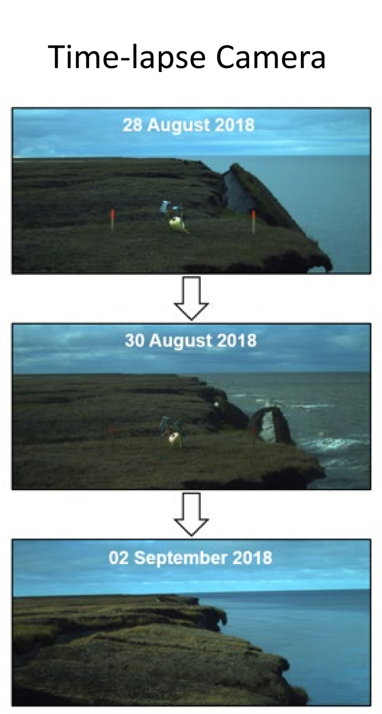


Block Collapse Timelapse

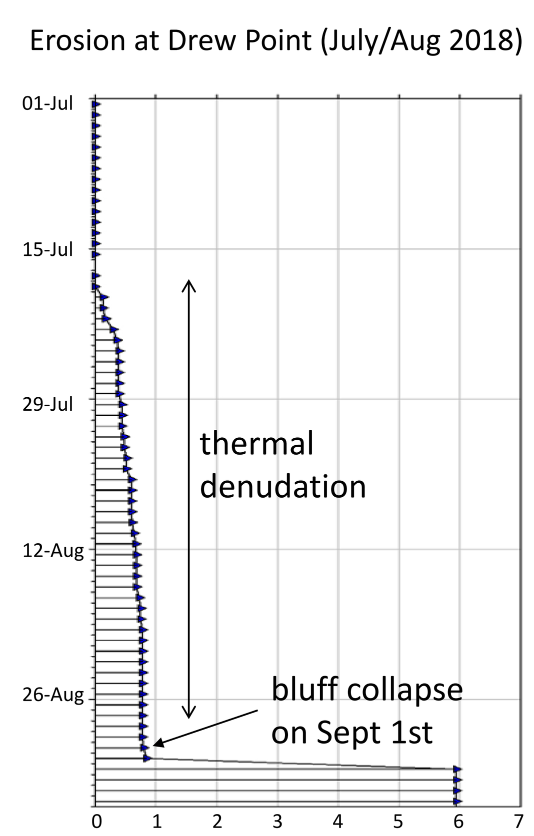


Block Collapse at Ice Wedge Surface

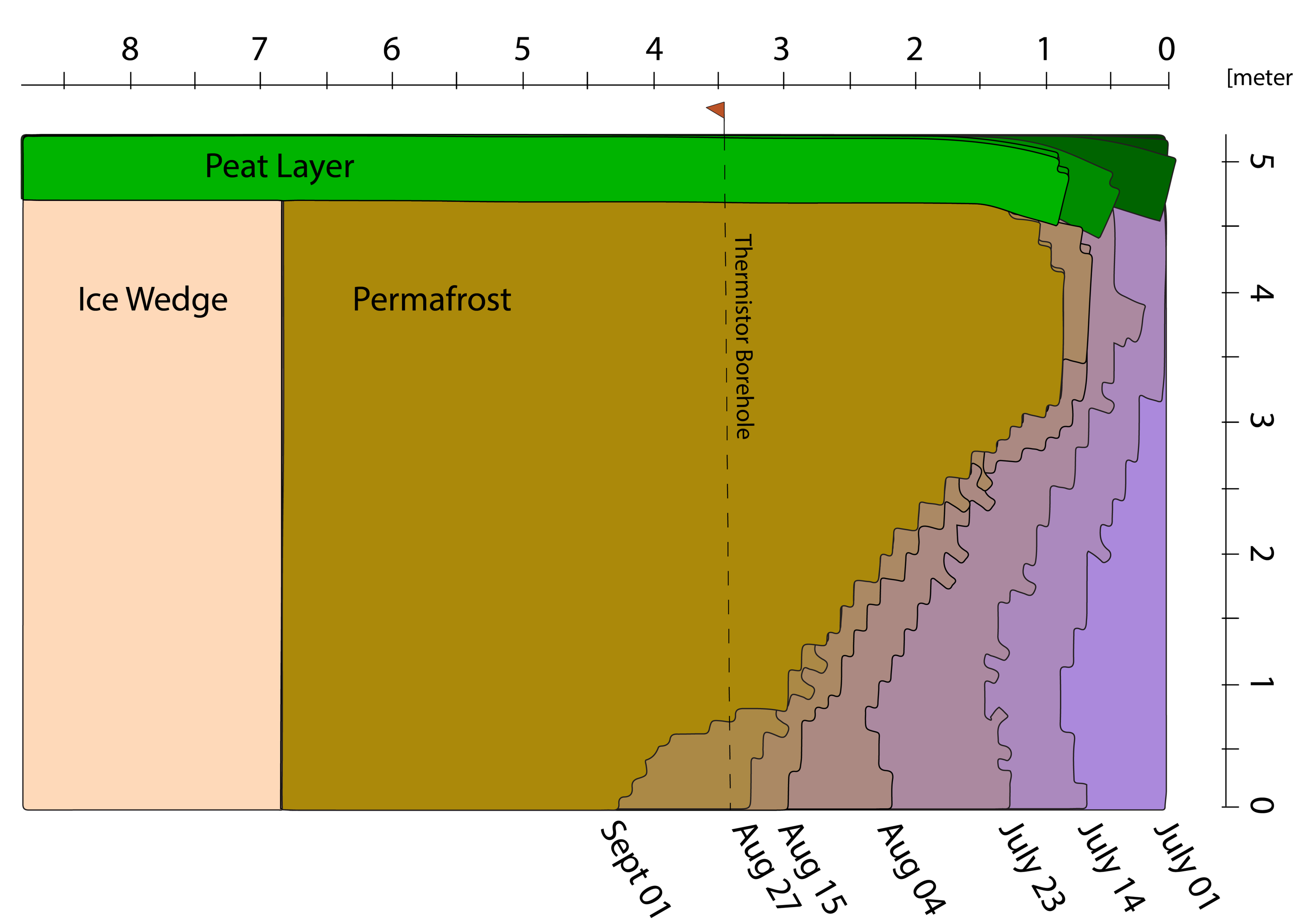




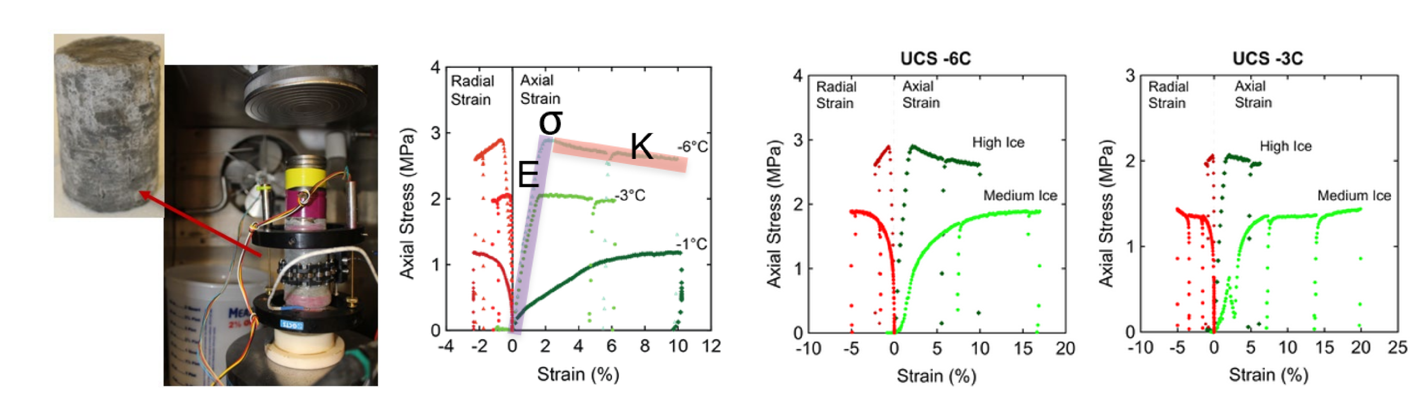
Niche development observed in thermistor data.

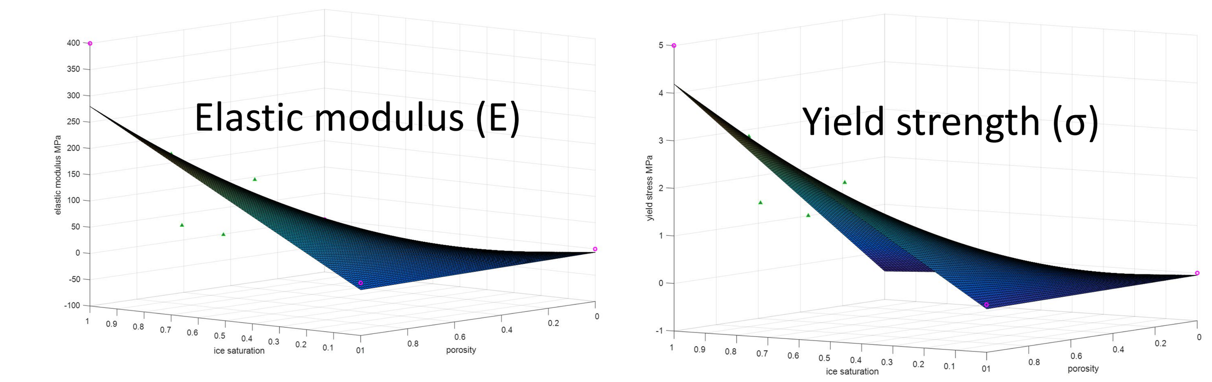


ACE Simulation Results for 2.5D Slice



Material Model Calibration to Experimental Data





Experimental results on permafrost core samples were analyzed to create fits for **E, K, σ** as a function of **ice saturation** and **porosity**.

For further information:
Frederick, J. M., A. Mota, I. Tezaur, and D. L. Bull (2021), A thermo-mechanical terrestrial model of Arctic coastal erosion, *Journal of Computational and Applied Mathematics*, Vol. 397, doi:10.1016/j.cam.2021.113533.
Bull et al. (2020), Arctic Coastal Erosion: Modeling and Experimentation, SAND2020-10223, *Sandia National Laboratories*, Albuquerque, NM.

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