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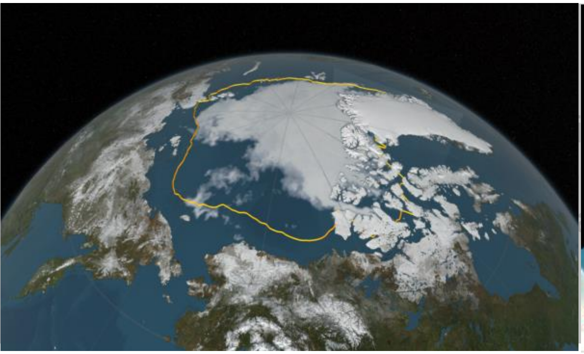
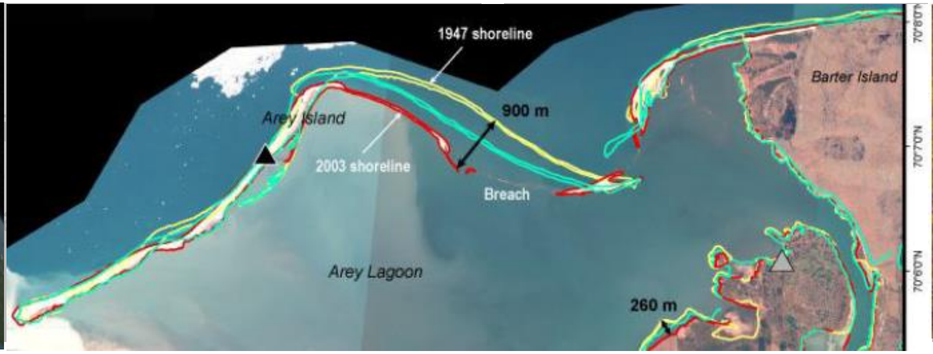


# Development of a strongly-coupled thermo-mechanical model of permafrost for the simulation of Arctic coastal erosion

Alejandro Mota, Jenn Frederick, Charles Choens, Diana Bull, **Irina Tezaur**

Sandia National Laboratories, U.S.A.

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

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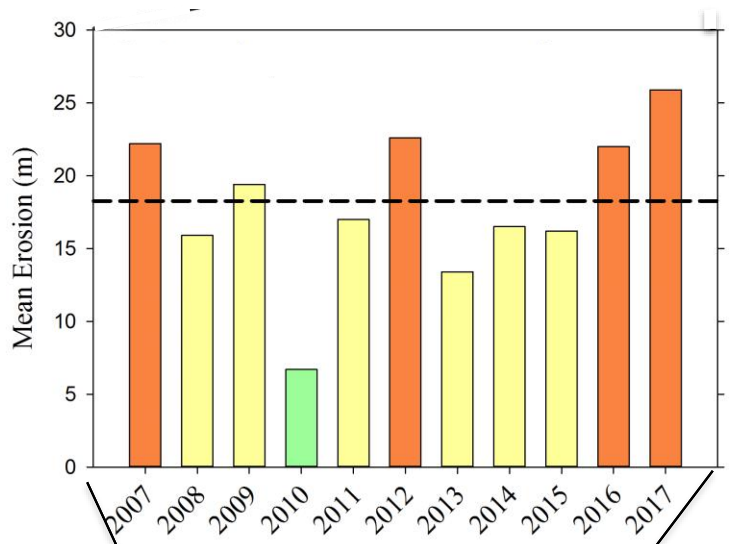
# Motivation

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

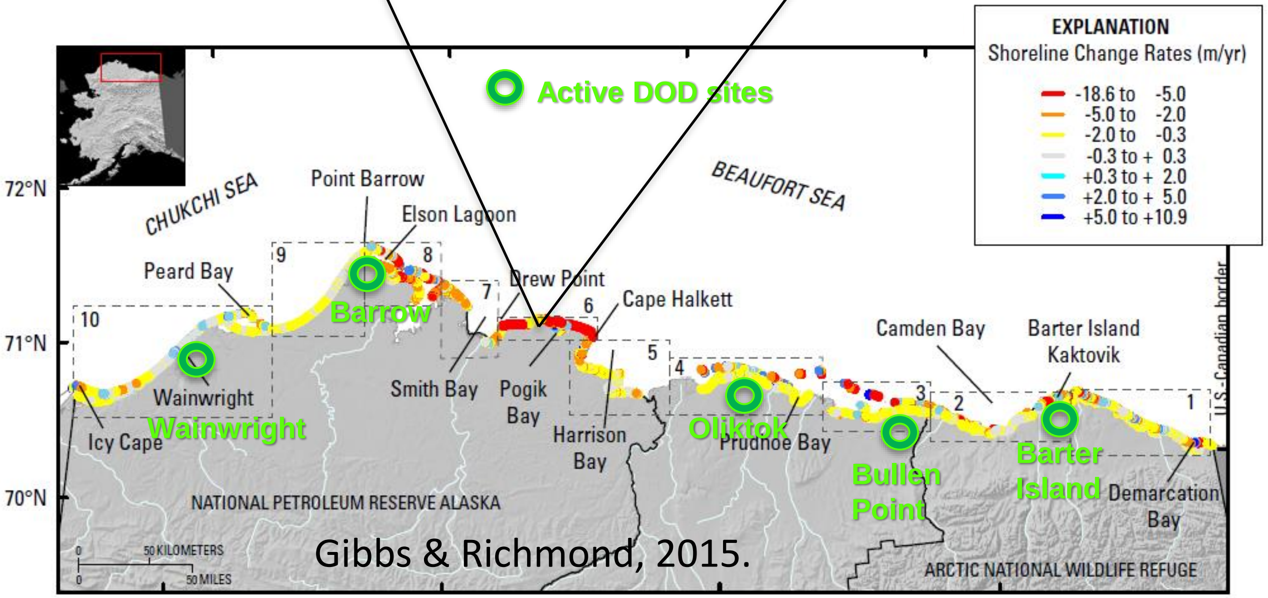
- Since 1979 **sea-ice** has lost 51% in area and 75% in volume
  - ➢ Increasing **ice-free season**
  - ➢ Increasing **wave energy** and **storm surge**
- Increasing **sea water** temperatures
- Warming **permafrost**
  - ➢ **Coastal erosion rates** in Alaskan Arctic among the **highest** in the world and **accelerating**.




~200 m (~2 football fields in length) in a decade!

***Erosion is threatening:***

- ➢ Coastal communities
- ➢ Coastal infrastructure
- ➢ Global carbon balance



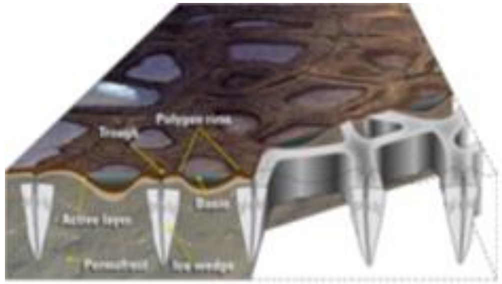

Gibbs & Richmond, 2015.

# Permafrost erosion

S

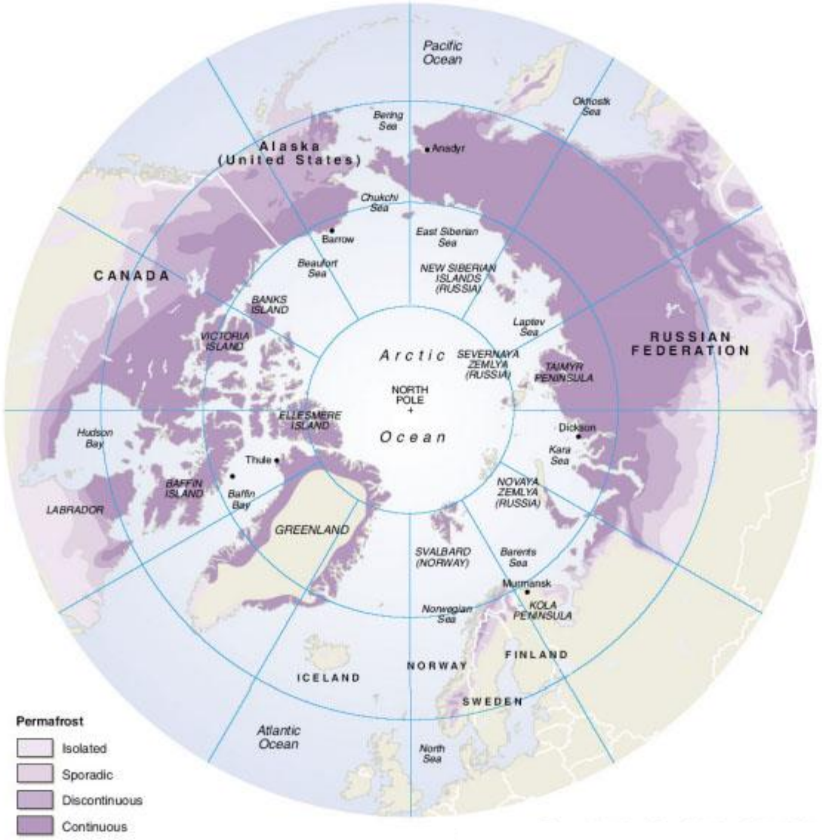
## *What is permafrost?*

- Ground that remains frozen for 2 or more consecutive years.
- Comprised of soil, rock, silt, clay and sand, held together by ice.
- 24% of ice-free land area in Northern Hemisphere and 85% of Alaska Greenland, Canada and Siberia sits on top of permafrost.



Martin *et al.* 2009.

*Left:* schematic illustrating formation of ice wedges and ice-wedge polygon landscapes. *Right:* map of permafrost distribution in Arctic




Brown *et al.* 1998.

## *Unique coastal permafrost erosion process in Arctic:*

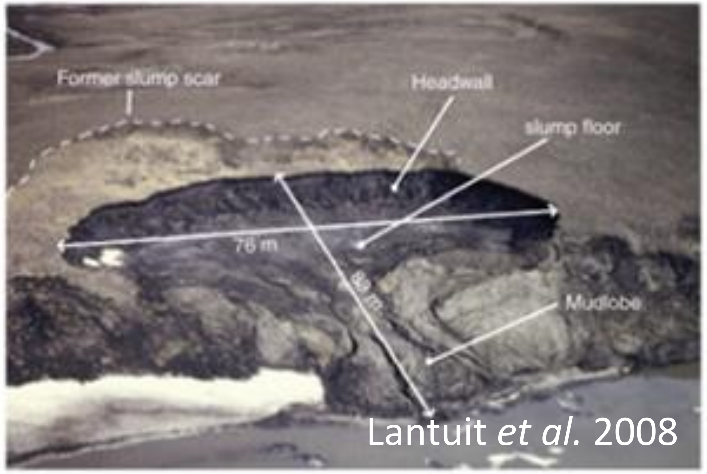
- Predominant geomorphology: **ice-wedge polygons**
  - Ice acts to **bind** unconsolidated soils in permafrost forming ice wedges.
  - Ice wedges **grow/expand** up to ms wide and 10s meters deep.
- Melting ice causes permafrost **failure**.
  - **Storm surges** accelerate ice melt by delivering **heat** to ice/permafrost***.**

* Thermo-abrasion: permafrost material is warmed by ocean and removed by mechanical action of waves.

# Permafrost failure mechanisms



- **Retrogressive thaw slumping**: a slope failure characterized by thaw of exposed ground ice and slumping of thawed soil, typically caused by thermo-denudation*.
- **Active layer detachment**: failures are translational landslides that occur in summer in thawing soil overlying permafrost, typically caused by thermo-denudation*.
- **Block failure**: a niche (recess at bluff base) progresses landward until the overhanging material fails in a shearing or toppling mode known as block failure.
  - Fallen blocks can disintegrate in the near-shore environment **within 1-2 weeks**!



Lantuit *et al.* 2008

Retrogressive thaw slumping

Lantuit *et al.* 2008

Active layer detachment


Ravens *et al. 2012*

Block failure

* Subaerial erosion triggered by thawing of permafrost bluffs that proceeds under the influence of gravity.

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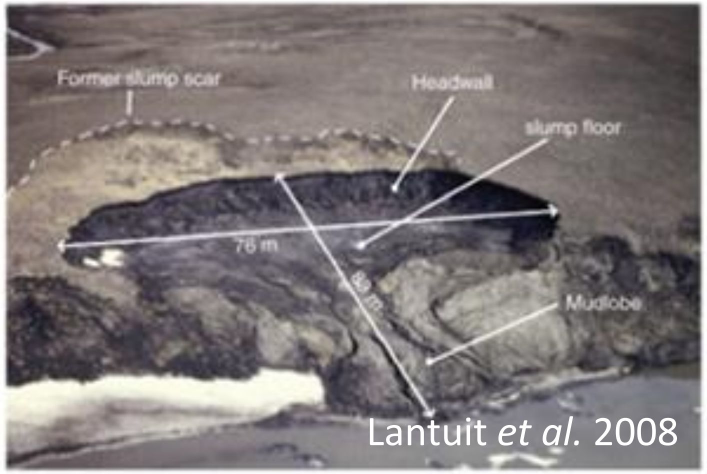


Retrogressive thaw slumping

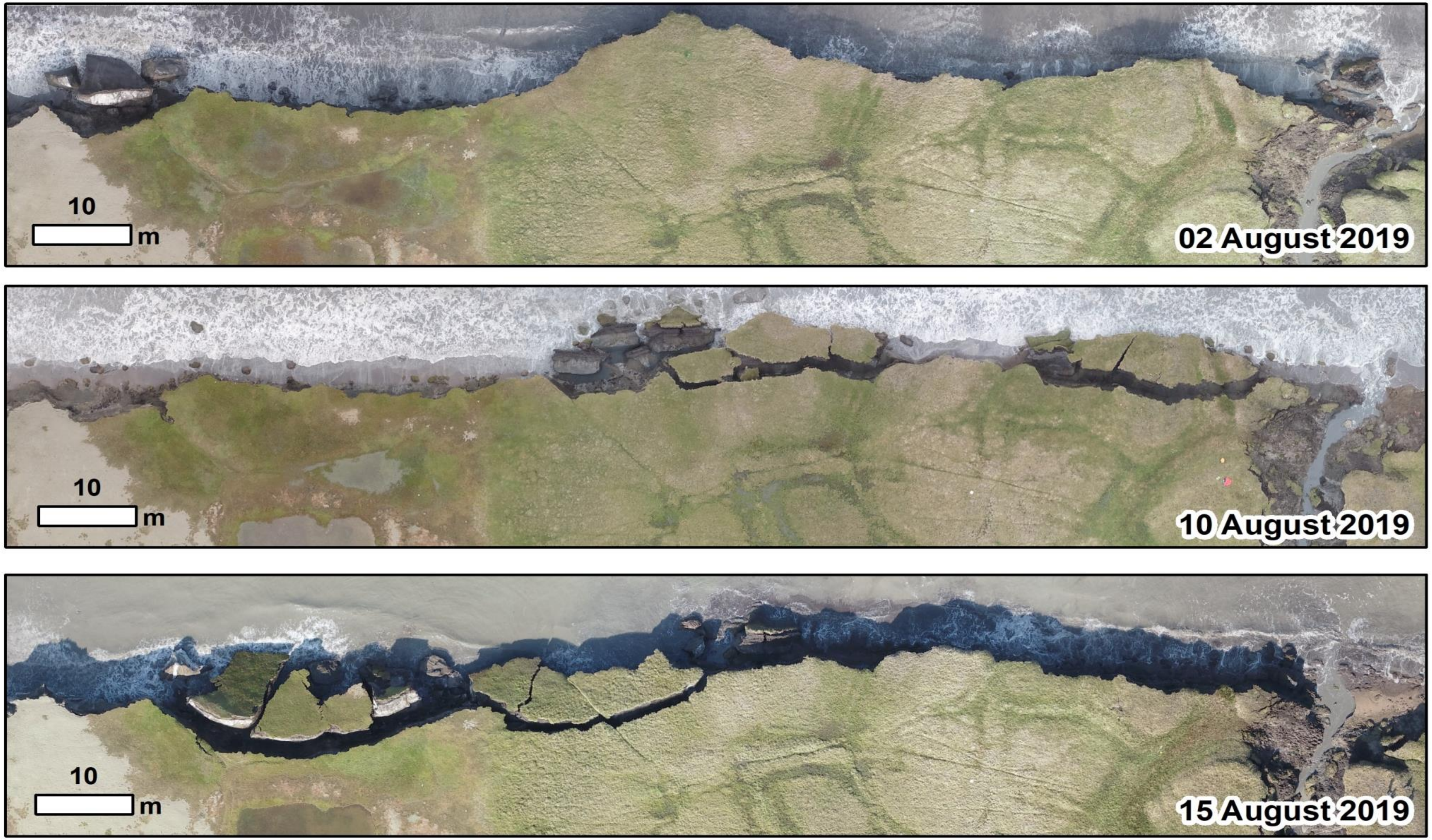
Active layer detachment

***Dominant failure mechanism in northern Alaska***

Block failure

* Subaerial erosion triggered by thawing of permafrost bluffs that proceeds under the influence of gravity.

# Example of bluff erosion during 2019 UAV surveys*



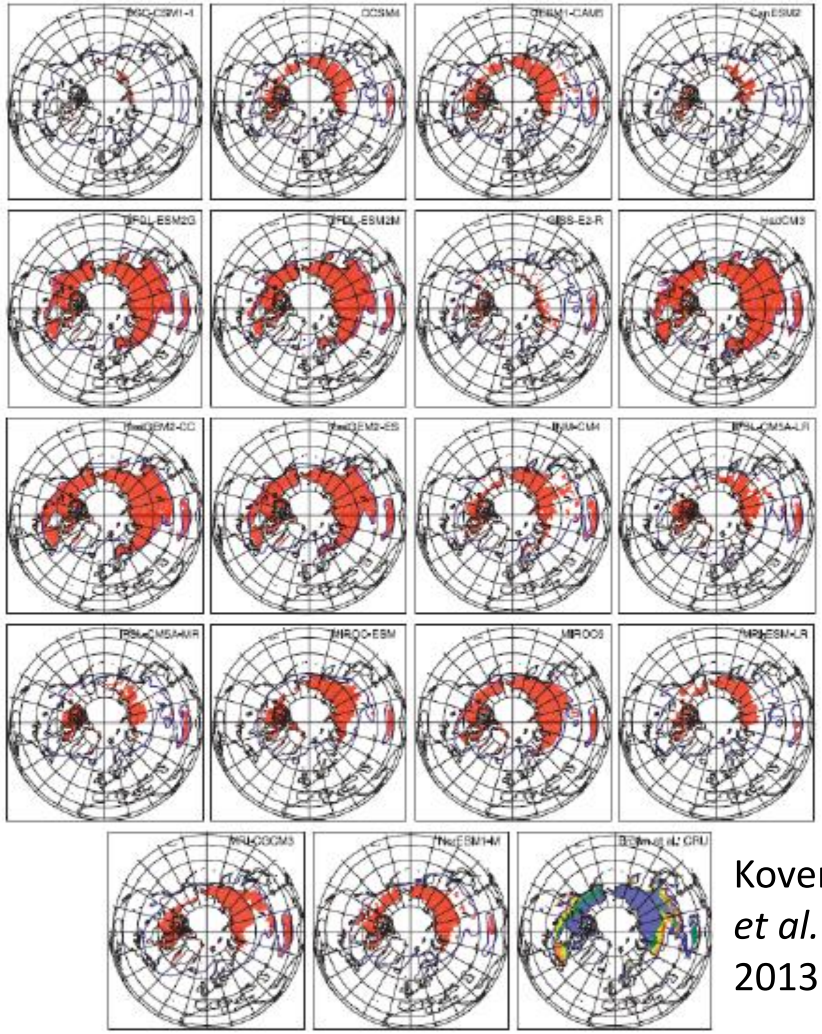

Fallen blocks can disintegrate in near-shore environment **within 1-2 weeks**!

*Images courtesy of Ben Jones, UAF

# State-of-the-art in permafrost modeling

When this project began in 2017, tools to **accurately predict** Arctic coastal erosion **did not exist**!

- Existing models* are **primitive**: trend projection, empirical relationships, 1D steady state heat flow,…
  - ➢ Primarily **thermal models** (no mechanics/deformation)
  - ➢ Most models assume **particular type** of **erosion** (e.g. block failure)
- Efforts have been put towards integrating permafrost models into **earth system models (ESMs):** CLM, VAMPERS, CryoGrid3, ...
- Modeling typically estimates BCs and **does not** account for geomorphologies or geophysics.
- Comprehensive **understanding** of erosion dynamics in the Arctic has **not yet emerged**.



Koven *et al.* 2013

To obtain an accurate, **predictive** Arctic coastal erosion model, a **coupling** of the influences of evolving **wave dynamics**, **thermodynamics** and **mechanics** must be developed.

* See (Frederick *et al.* 2016), Chapter 5, for extensive overview.

# Proposed solution

Goal of the **Arctic Coastal Erosion (ACE)** project is to deliver a **field-validated predictive model** of **thermo-abrasive erosion** for the **permafrost Arctic coastline**

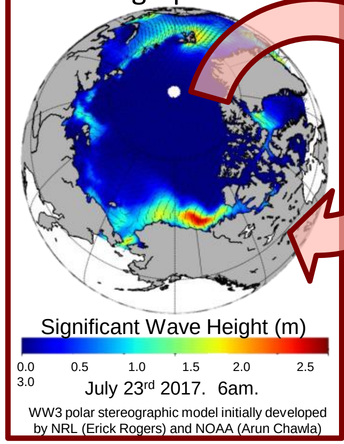
2018-2019

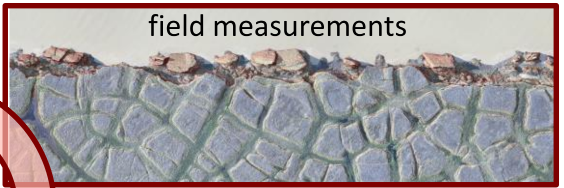
**Micro-scale Model**

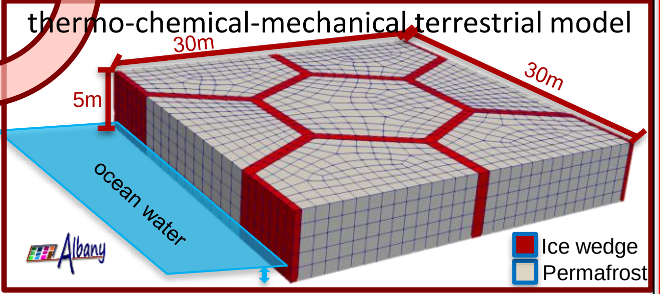
10's of meters & storm duration

- ***Multi-physics finite element model*** of an archetype of the coastline coupled with high-fidelity model of storm intensities
  - Input variables define geomorphology & geophysics
  - Plastic deformation model of material (J2 class)
  - Geomechanical testing to determine coupled thermal-mechanical strength characteristics
  - Time-varying ocean BCs (water level, temp, salinity)
  - Eroded sediment and biogeochemical flux tracking

***This talk***



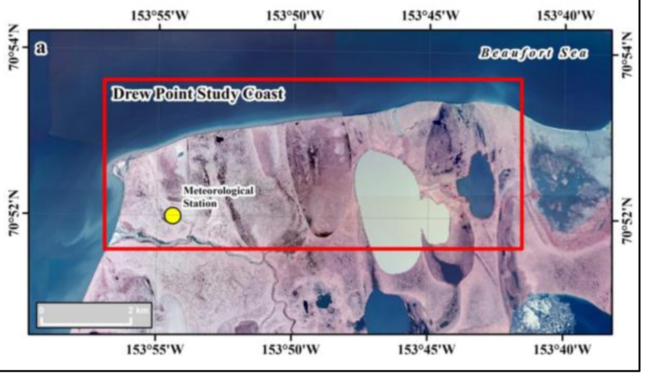




2019-2020

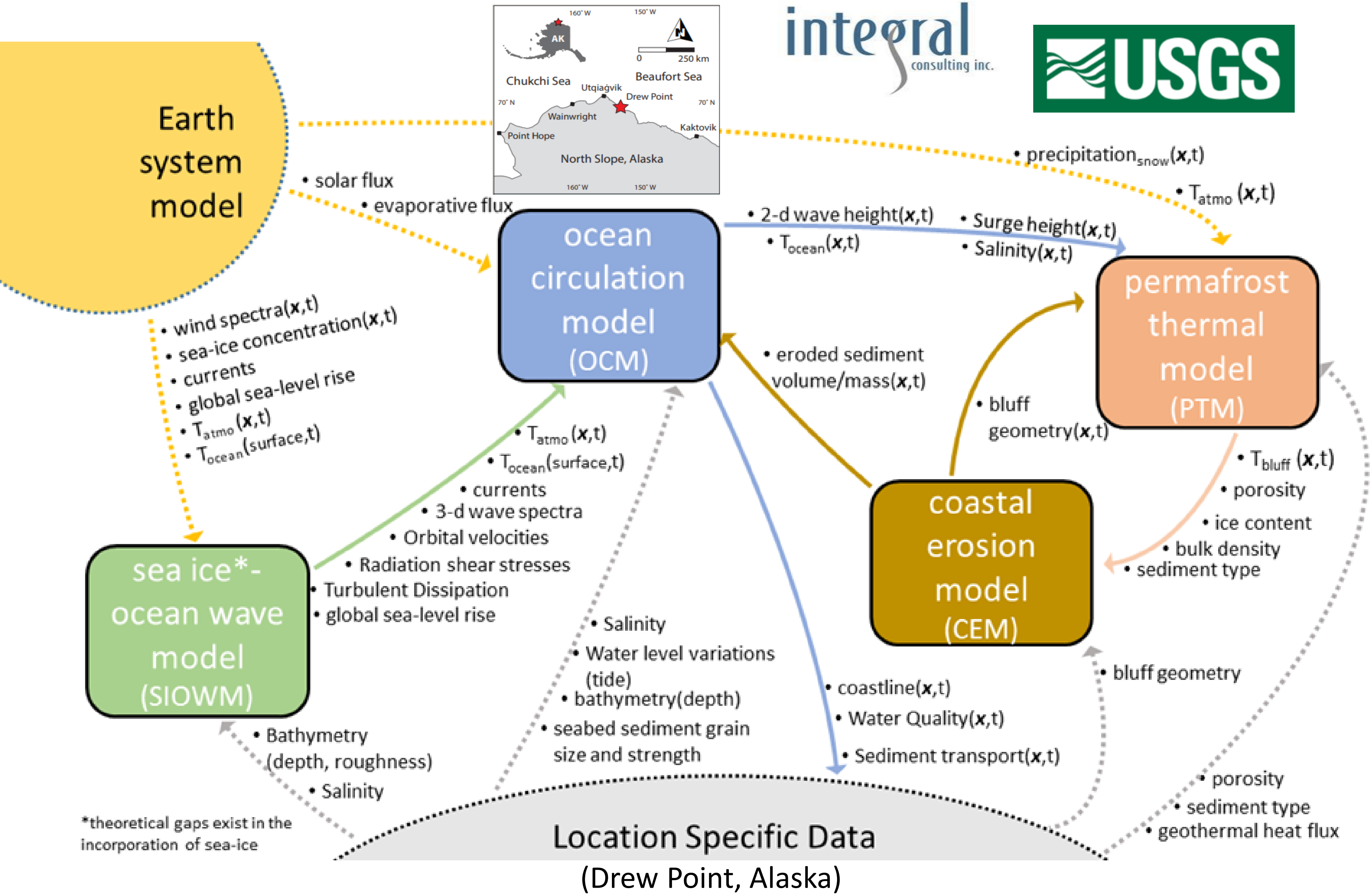
**Meso-scale Model**

10's of km's & seasonal duration

- A "catalog" of micro-scale models that represent the statistical distributions of input variables along a ~10km stretch of coastline.
  - Probability distribution functions of geomorphology and geophysics used to weight erosion output
    - Will validate approach with decade long annual measurements at Drew Point.
  - Evaluating ocean "exposure metrics" to represent time-varying ocean



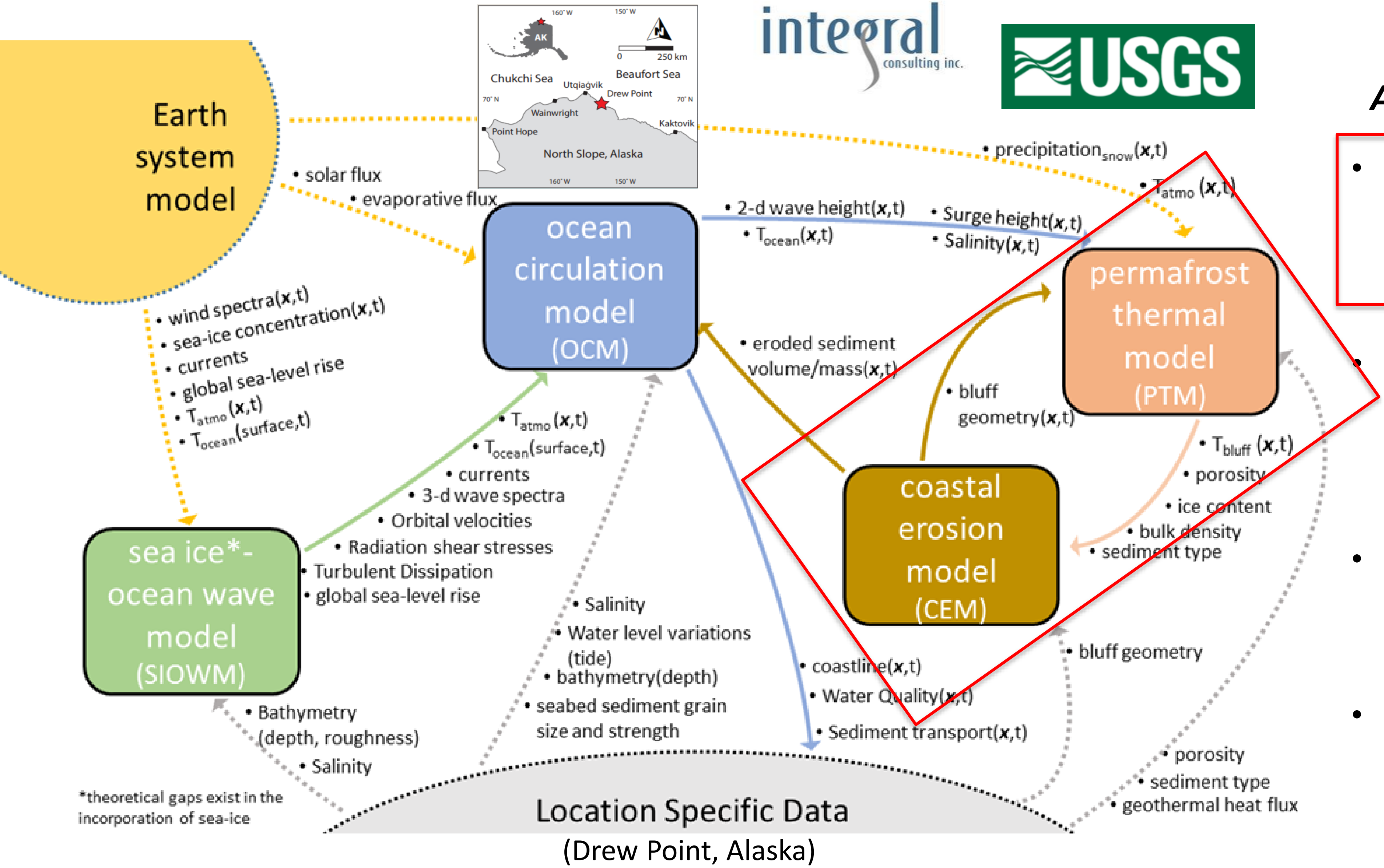
# ACE Model Component Coupling




***ACE project has many pieces!***

- **Terrestrial model**: thermo-mechanical coupled FEM model that can simulate transient niche development.
- **Oceanographic model**: WW3 + SWAN + Delft3D wave models for providing oceanic BCs (ocean temp/height) to terrestrial model.
- **Geomechanical testing**: for characterization of permafrost parameters in terrestrial model.
- **Field campaign**: offshore oceanographic measurements, bathymetric survey, niche measurements, etc.

# ACE Model Component Coupling

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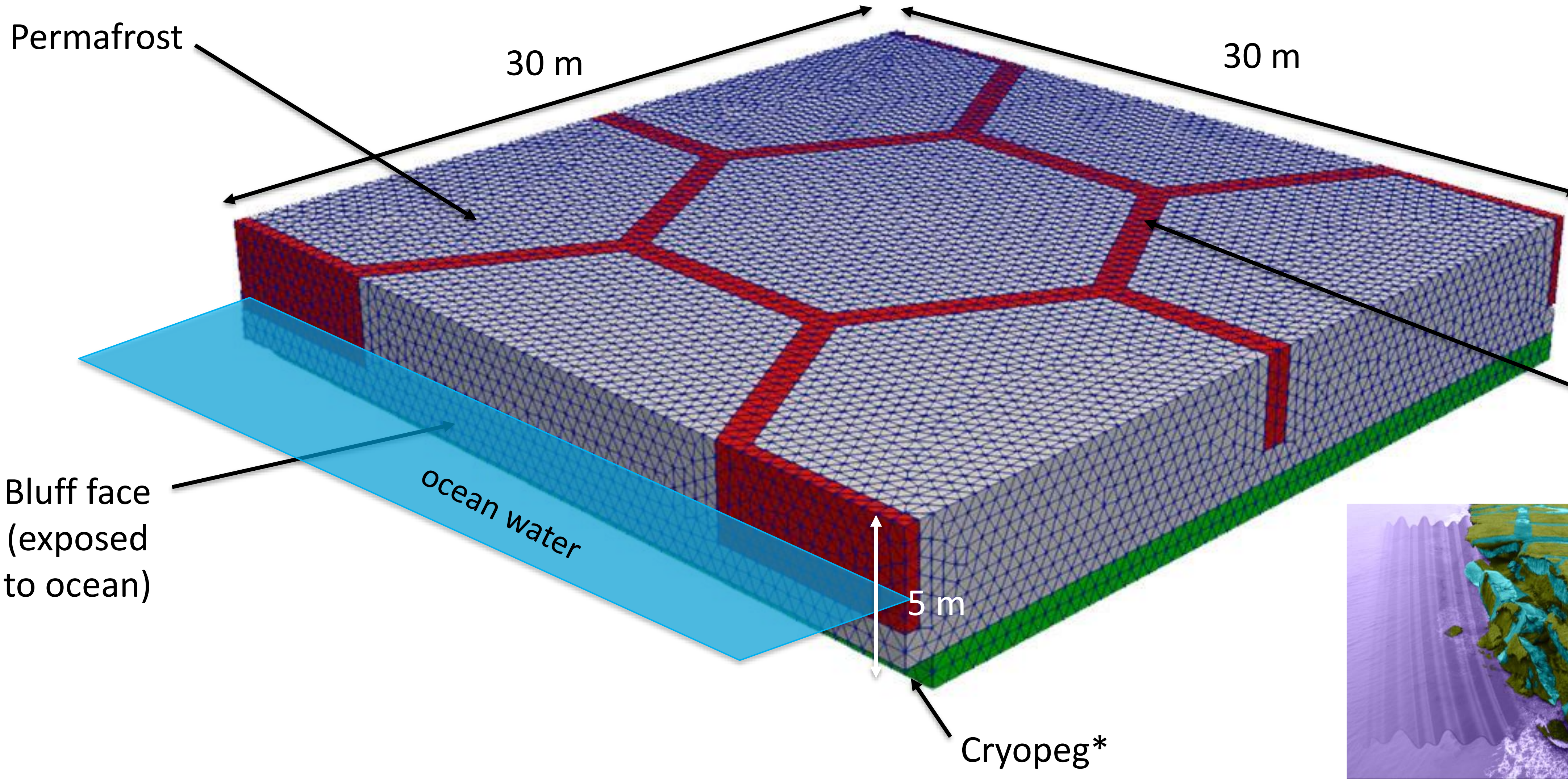
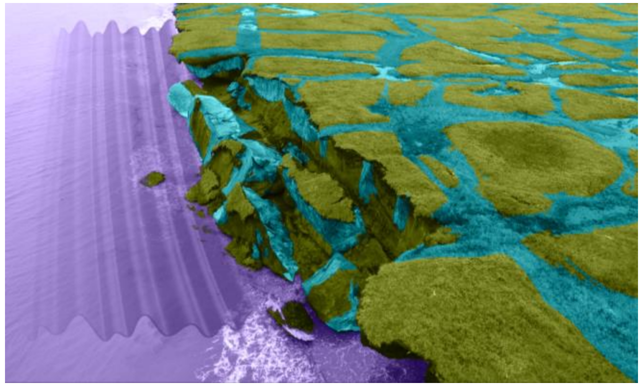
# Anatomy of a canonical computational domain



* Layer of unfrozen ground that is perennially cryotic (forming part of the permafrost) in which freezing is prevented.

# Mechanical model

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

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

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

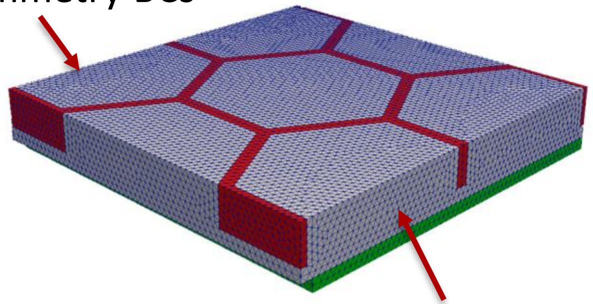
  - Computes ***displacements*** and ***new computational geometry*** (following erosion)

- ***J2 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 w/ plastic behavior.

- ***Symmetry boundary conditions*** on lateral sides

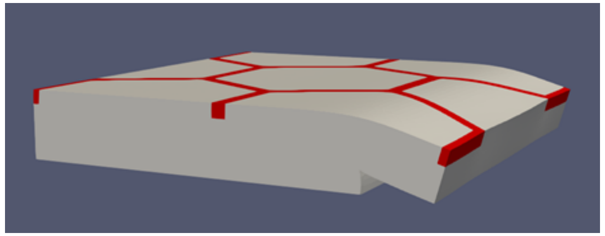
- ***Yield stress***: $\sigma_0(T) := S_s\sigma_Y^{\mathrm{soil}} + S_f f(T)\sigma_Y^{\mathrm{ice}}$
  - Used in erosion failure criteria

$f$: ice saturation ($\in [0,1]$)
$\sigma_Y^{\mathrm{soil}}/\sigma_Y^{\mathrm{ice}}$: yield stress of soil/ice
$S_s/S_f$: soil/ice volume fraction



# Erosion failure criteria

- **Erosion criterion:** when material exposed to water reaches a critical exposure time.
- **Stress criterion:** when material reaches a critical value of the yield stress.
- **Kinematic criterion:** when material has tilted excessively, it is assumed to have fallen as part of block erosion.



Once **failure criterion** is reached, “failed” elements are **removed** from mesh.

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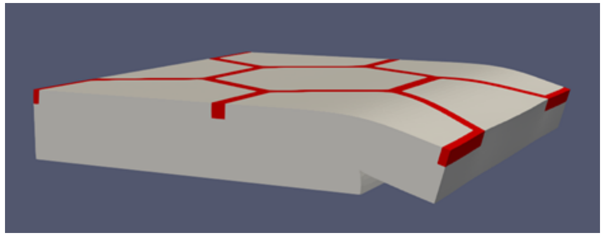

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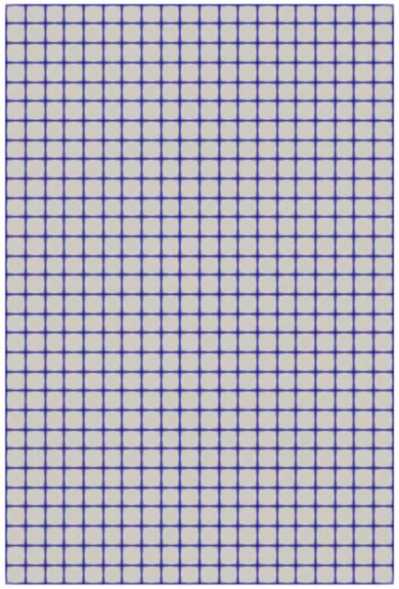

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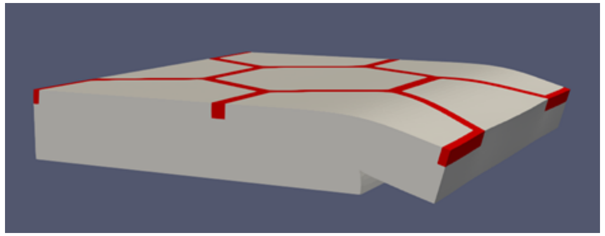

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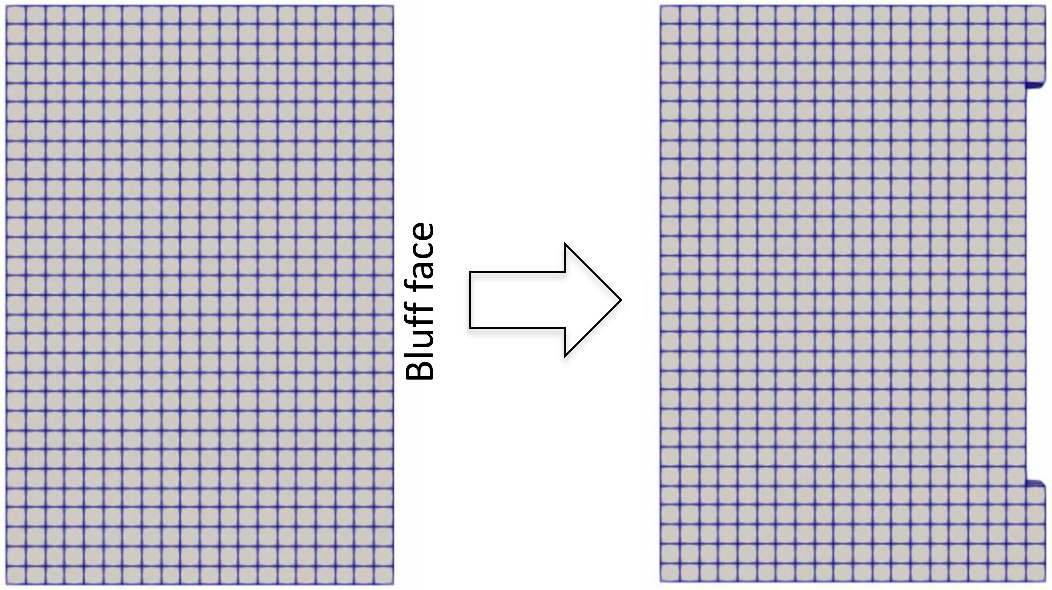

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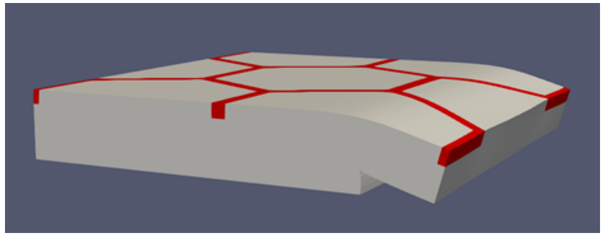

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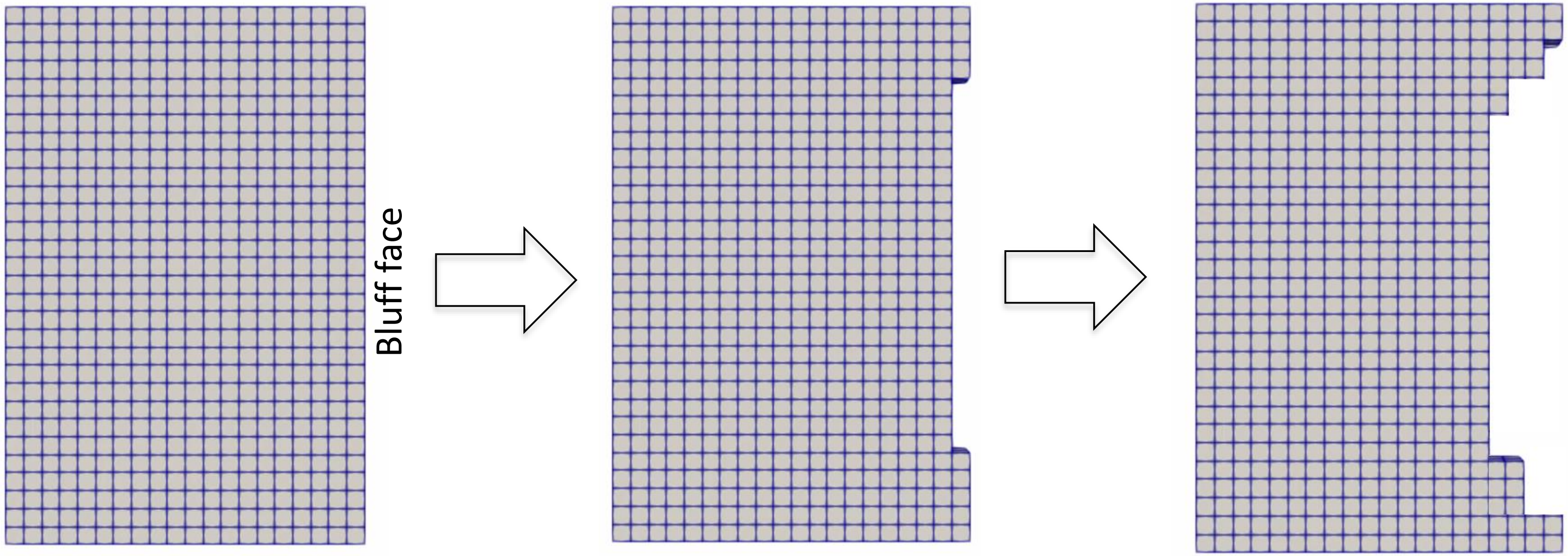

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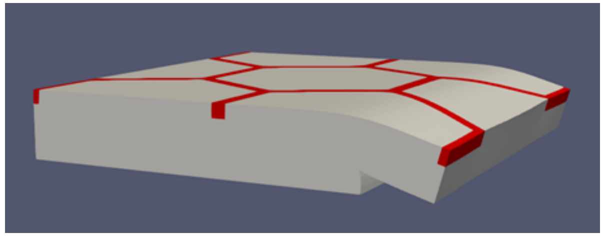

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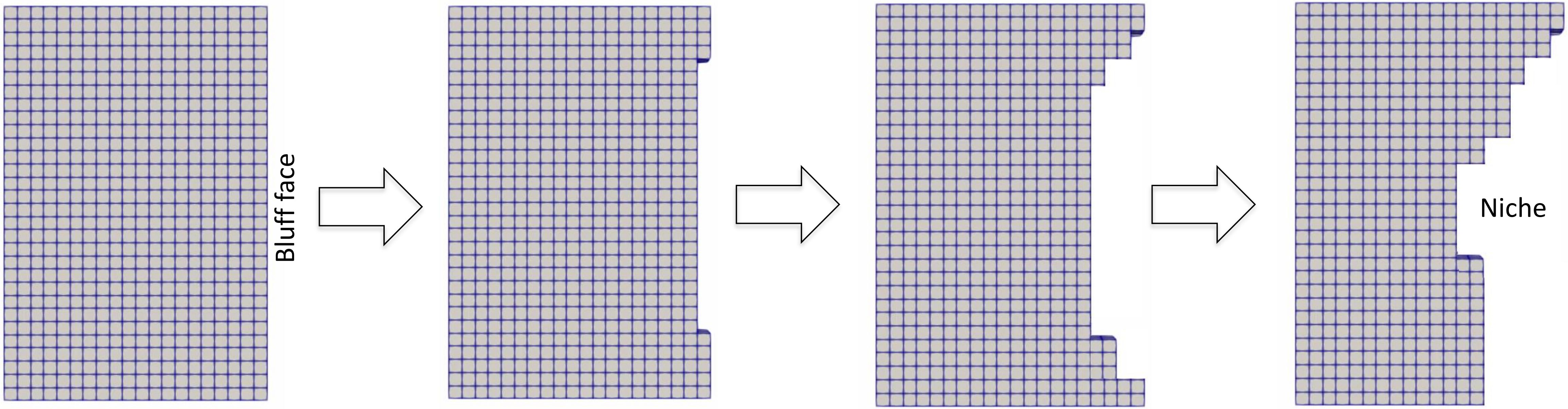
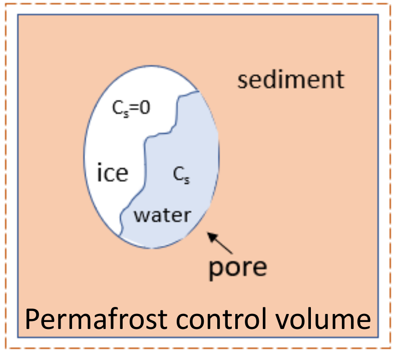


# Thermal model

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

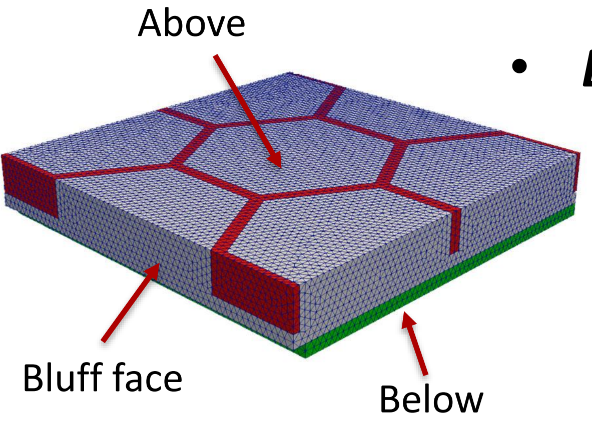
$$(\overline{\rho c_p} + \widetilde{\Theta})\frac{\partial T}{\partial t} = \nabla \cdot (\boldsymbol{K} \cdot \nabla T)$$



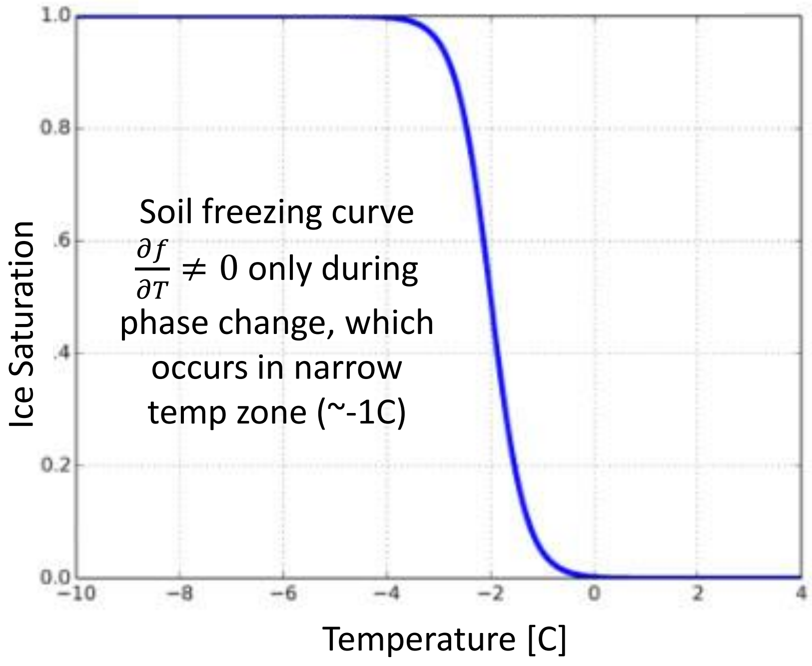

where $\widetilde{\Theta} \coloneqq \rho_f L_f \frac{\partial f}{\partial T}$ incorporates phase changes through soil freezing curve, $\frac{\partial f}{\partial T}$.

➢ Computes ***temperature*** $T$ and ***ice saturation*** $f$

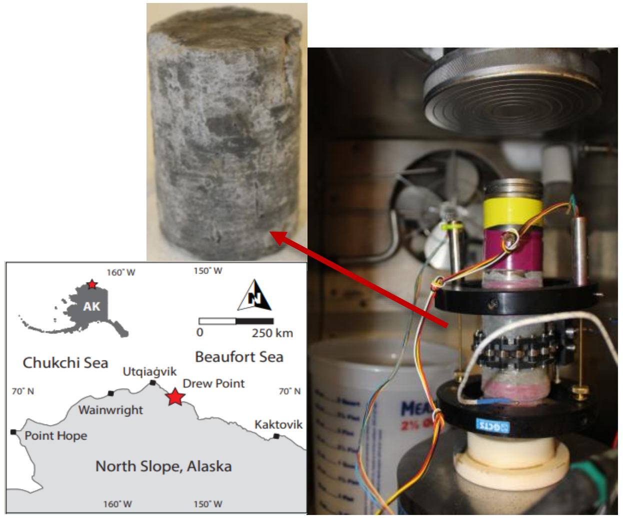
$\bar{\rho}$: density from mixture model
$\overline{c_p}$: specific heat from mixture model
$\boldsymbol{K}$: thermal diffusivity tensor
$\rho_f$: ice density
$L_f$: latent heat of water-ice phase change
$f$: ice saturation ($\in [0,1]$)
$\frac{\partial f}{\partial T}$: soil freezing curve (depends on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

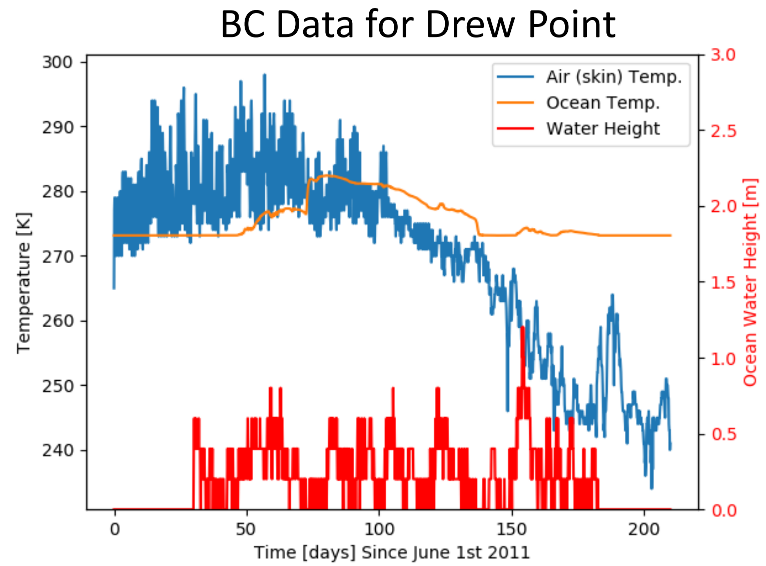



- ***Boundary conditions*** (from wave model/data)
  - ➢ Local geothermal heat flux from below
  - ➢ Mean annual air temp from above
  - ➢ Air/ocean temp at bluff face



# Parameters & inputs




***Parameters estimated from lab experiments:***

- Elastic modulus, Poisson's ratio, yield strength
- Sand/silt/clay fractions with depth
- Porosity with depth

***Parameters from literature:***

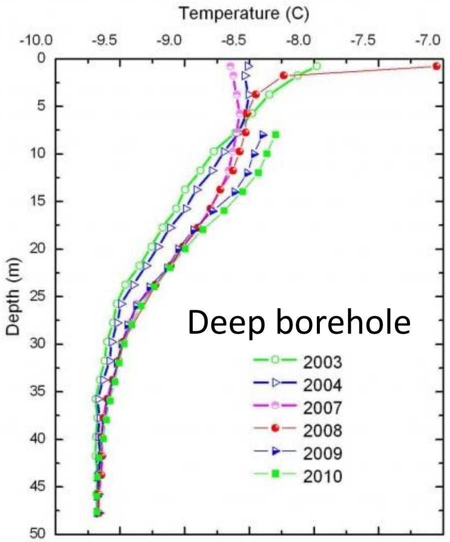
- Ice/water/sediment densities, thermal conductivities, heat capacities
- Freezing curve/width as function of sediment type
- Bluff salinity with depth

***Parameters estimated from observational data at Drew Point, AK:***

- Skin temp w/ time, initial bluff temp (USGS weather station data)
- Geothermal heat flux (borehole at Barrow, AK)
- Polygon dimension, ice wedge thickness and depth, bluff height, living organic layer thickness (Aug. 2019 field campaign)

***Parameters from wave model (WW3+SWAN+Delft3D):***

- Ocean temperature, salinity and sea-level w/ time (for thermal BCs)

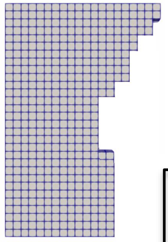



# Coupled thermo-mechanical formulation

***Potential key advantages:***

- Tightly coupled strength and thermo-chemical states
- Failure modes develop from constitutive relationships in FEM model (no empirical relationships!)
- 3D unsteady heat flow can include chemistry

***Unique characteristic of coupled model***: coupling happens at the level of material model

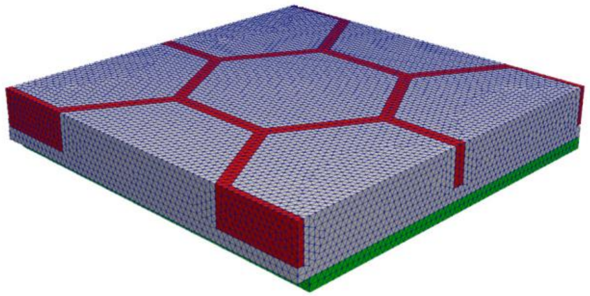


Eroded geometry

***Thermal:***

***Inputs:*** geometry, sediment type, ice volume, water volume, pore size, salinity

***Outputs:*** temperature field, ice saturation



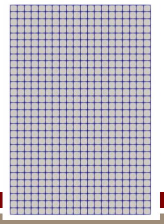
Albany

Ice saturation

***Mechanical:***

***Inputs:*** ice saturation, strength relationship as function of thermal state, stress-strain relationships of permafrost and ice

***Outputs:*** displacements, eroded geometry



# Finite element implementation within *Albany*

The ***thermo-mechanical Arctic Coastal Erosion (ACE)*** model is implemented within the ***LCM project*** in Sandia's open-source parallel, C++, multi-physics, finite element code, ***Albany***.

- ***Component-based*** design for rapid development.
- Contains a wide variety of ***constitutive models***.
- Extensive use of libraries from the open-source ***Trilinos*** project.
  - ➢ Use of the ***Phalanx*** package to decompose complex problem into simpler problems with managed dependencies.
  - ➢ Use of the ***Sacado*** package for ***automatic differentiation.***
- Coupled to the ***DOE's Energy Exascale Earth System Model (E3SM)*** through Albany Land-Ice (ALI) component.
- All software available on ***GitHub***.

https://github.com/SNLComputation/LCM

https://github.com/trilinos/trilinos

# Mechanics-only simulation*

Sandia National Laboratories

frontiers in Earth Science

ORIGINAL RESEARCH
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## Geometric and Material Variability Influences Stress States Relevant to Coastal Permafrost Bluff Failure

*Matthew A. Thomas*[1*†], *Alejandro Mota*[2], *Benjamin M. Jones*[3], *R. Charles Choens*[2], *Jennifer M. Frederick*[2] and *Diana L. Bull*[2]

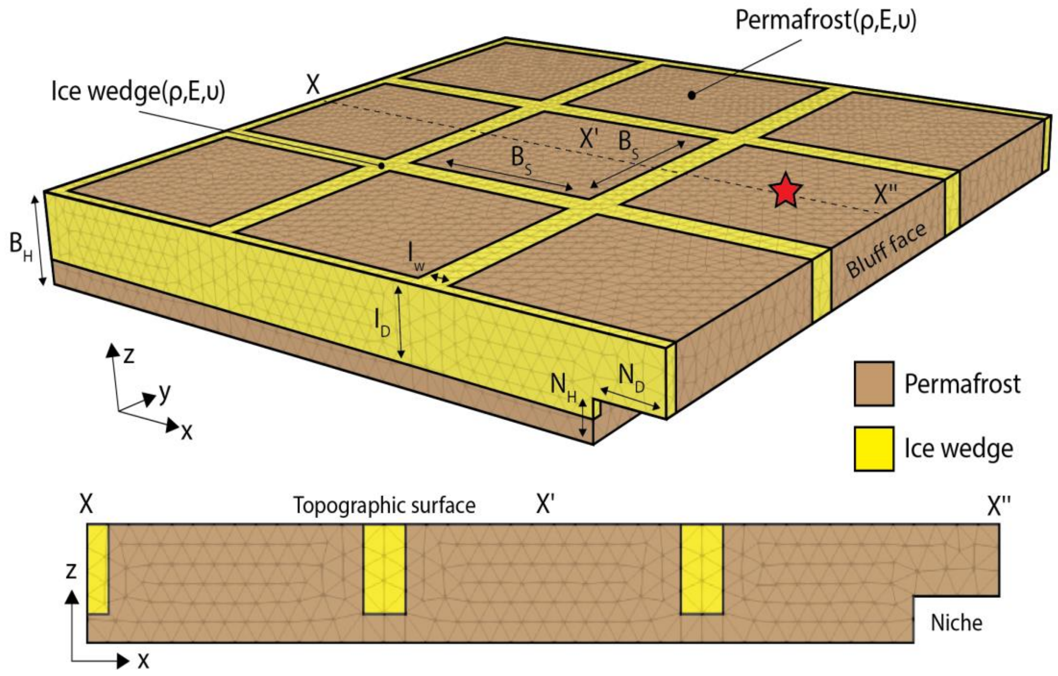
[1] U.S. Geological Survey, Geologic Hazards Science Center, Golden, CO, United States, [2] Sandia National Laboratories, Albuquerque, NM, United States, [3] Institute of Northern Engineering, College of Engineering and Mines, University of Alaska Fairbanks, Fairbanks, AK, United States

Scientific knowledge and engineering tools for predicting coastal erosion are largely confined to temperate climate zones that are dominated by non-cohesive sediments. The pattern of erosion exhibited by the ice-bonded permafrost bluffs in Arctic Alaska, however, is not well-explained by these tools. Investigation of the oceanographic, thermal, and mechanical processes that are relevant to permafrost bluff failure along Arctic coastlines is needed. We conducted physics-based numerical simulations of mechanical response that focus on the impact of geometric and material variability on permafrost bluff stress states for a coastal setting in Arctic Alaska that is prone to toppling mode block failure. Our three-dimensional geomechanical boundary-value problems output static realizations of compressive and tensile stresses. We use these results to

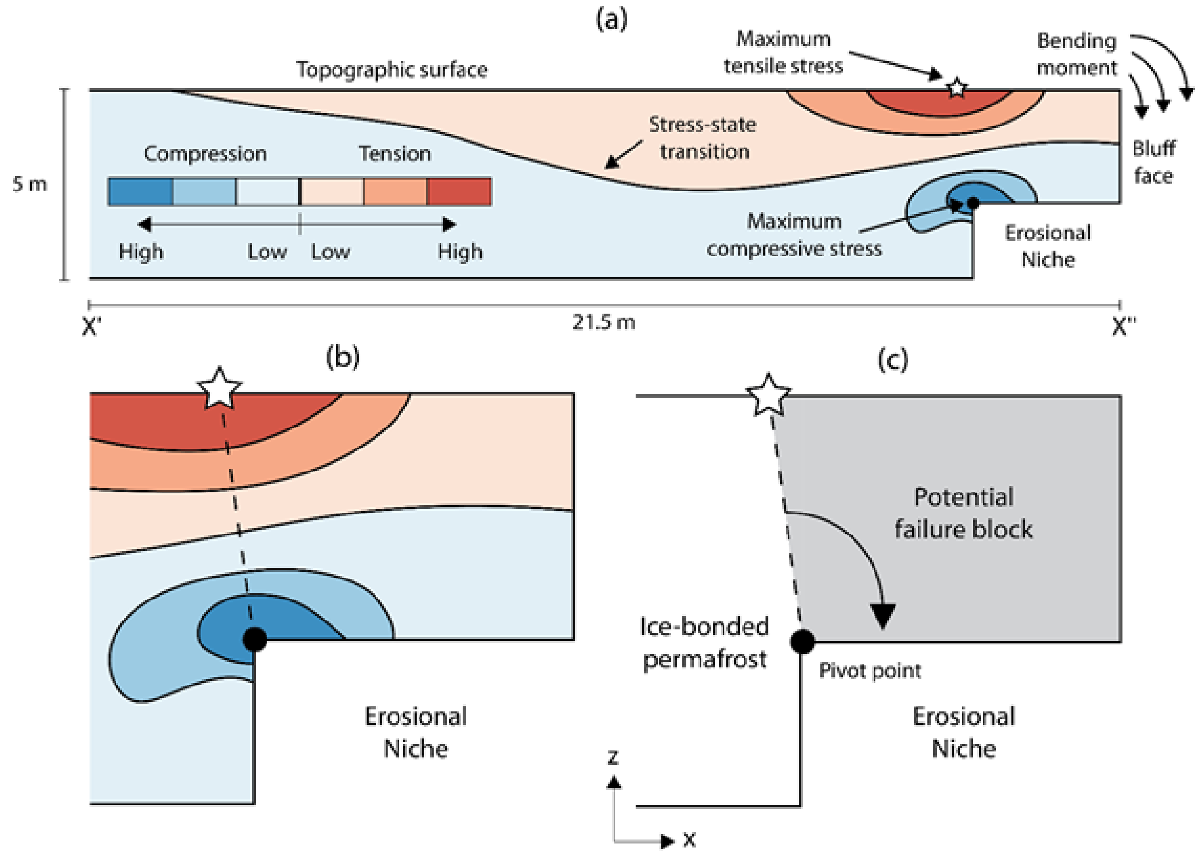
From recently-published *Frontiers in Earth Science* special issue.

* M. Thomas *et al.* *Frontiers in Earth Science* 8, April 2020.

# Mechanics-only simulation*



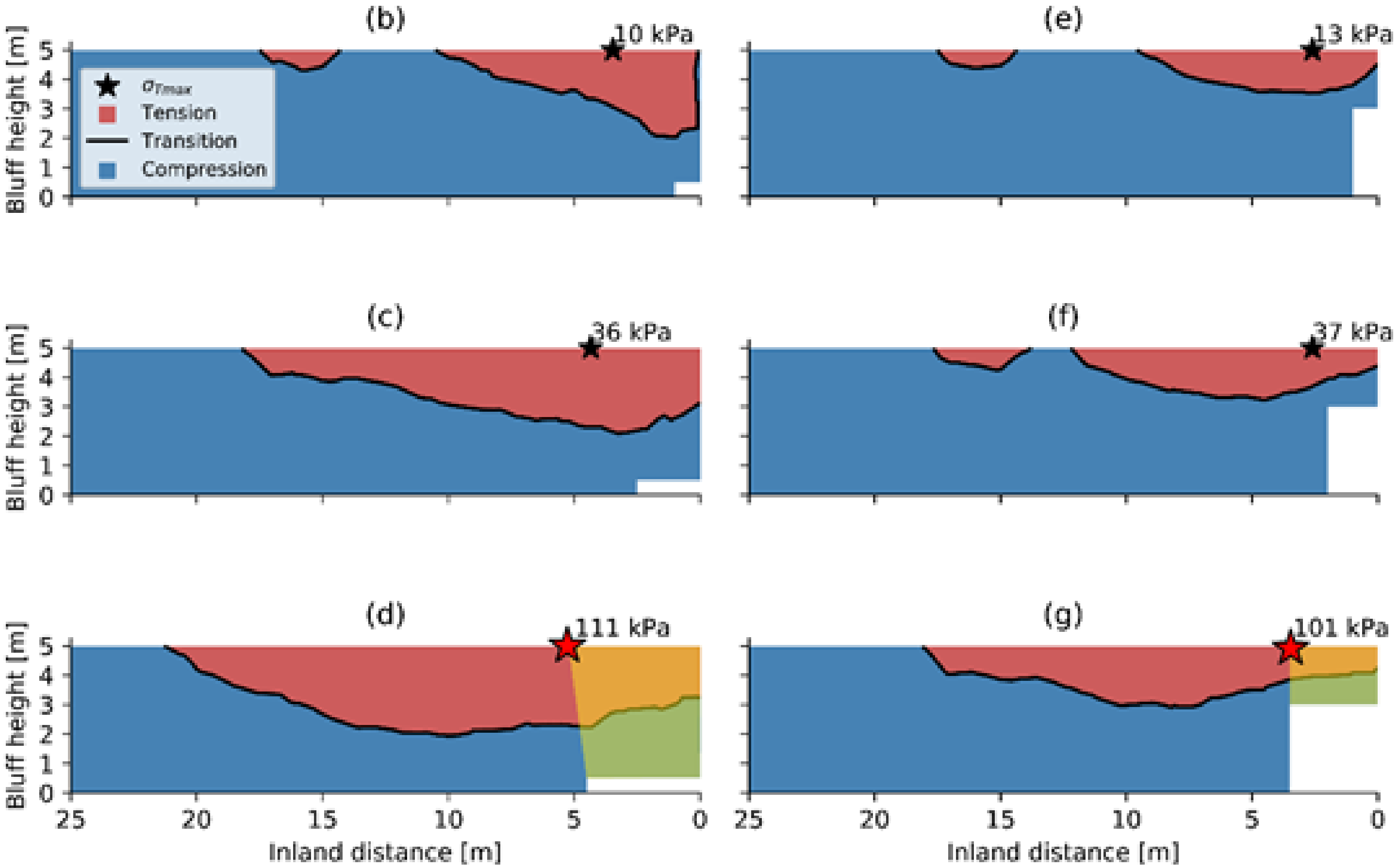

- **3D elastic mechanics-only** simulations assessed impact of **bluff geometry** and **material variability** on stress states leading up to bluff failure
  - ➢ Only load is gravitational.




- Simulations facilitated examination of **stress patterns** within bluff and identification of **location** and **magnitude** of **max tensile stress** ($\sigma_{T_{\max}}$)

# Mechanics-only simulation*: main takeaways

**Niche dimension** affects location and magnitude of simulated **max tensile stress (**$\sigma_{T_{\max}}$**)** more than the bluff height, ice wedge polygon size, ice wedge geometry, bulk density and Poisson's ratio




- Inland extent of niche was advanced for 6 erosional niche heights from 0.1-3 m

**Taller** and **narrower** erosional **niches** promote smaller failure masses compared to those with shorter and deeper niches

- Lower bound for tensile stress from lab measurements: 100 kPa
- Orange/green shading highlights potential failure areas.

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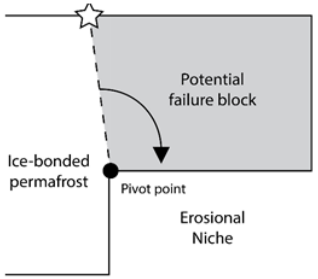
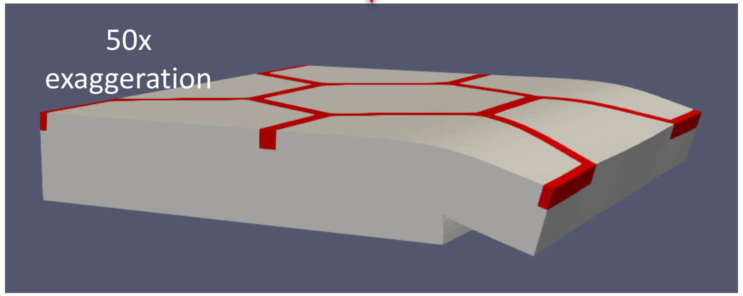
# Mechanics-only simulation*: main takeaways

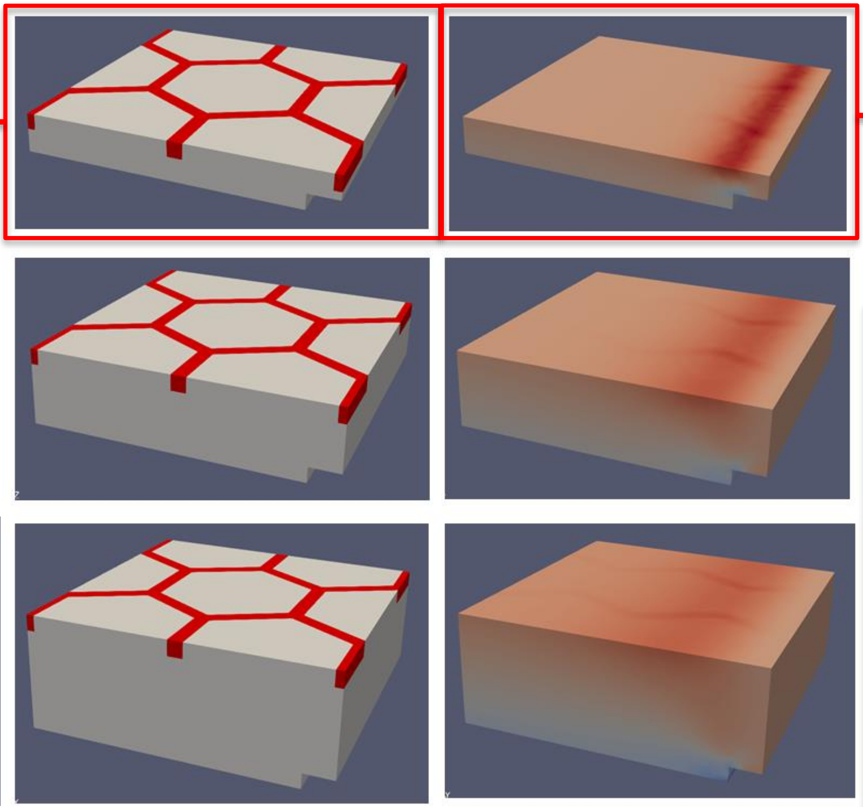
Sandia National Laboratories

**Taller** and **narrower** erosional **niches** promote smaller failure masses compared to those with shorter and deeper niches

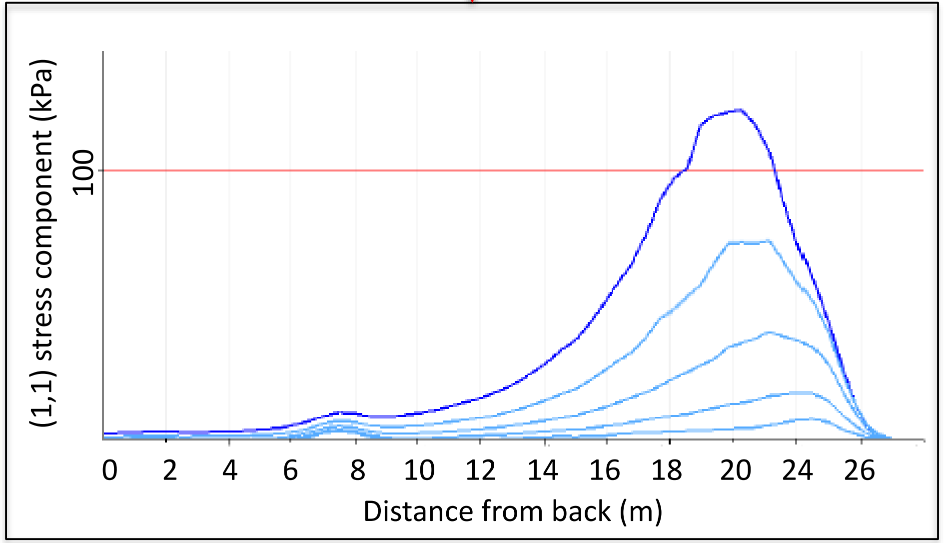
As niche advances into the block, an overhanging section in the block acts as ***cantilever***.



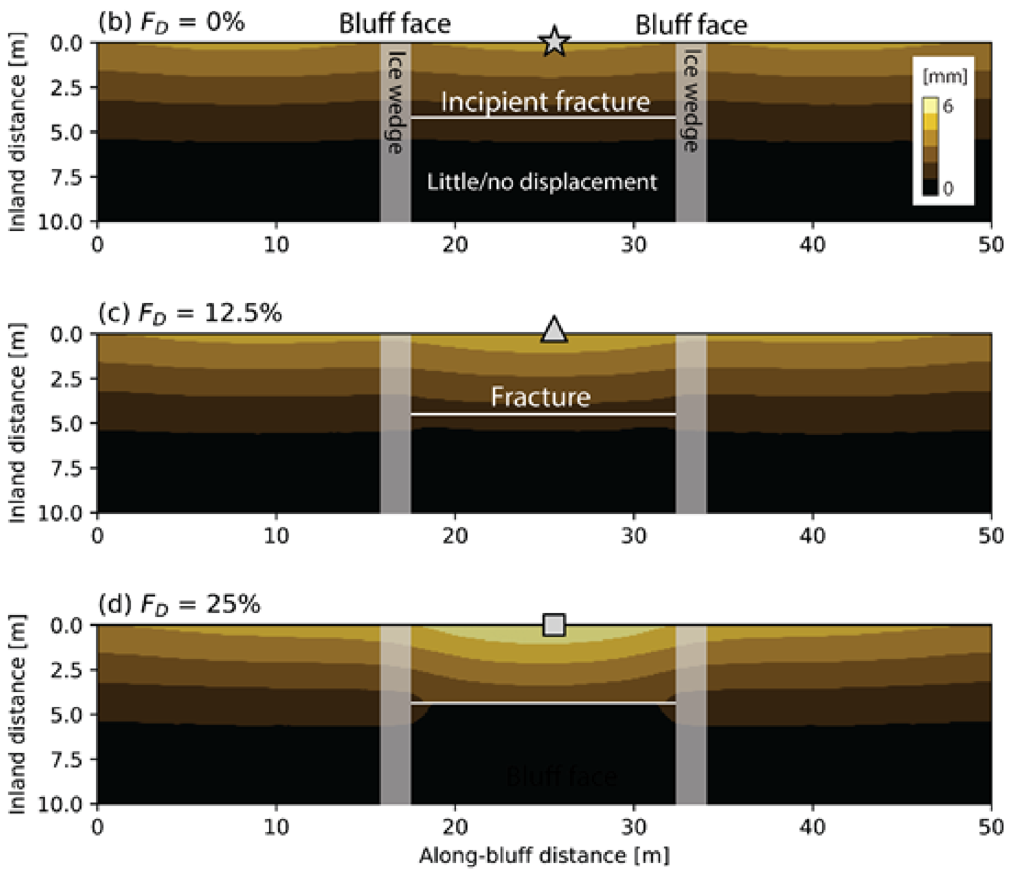
Highest ***tensile stresses*** develop on top surface where cantilever meets rest of block




* M. Thomas *et al.* *Frontiers in Earth Science* 8, April 2020.

# Mechanics-only simulation*: main takeaways

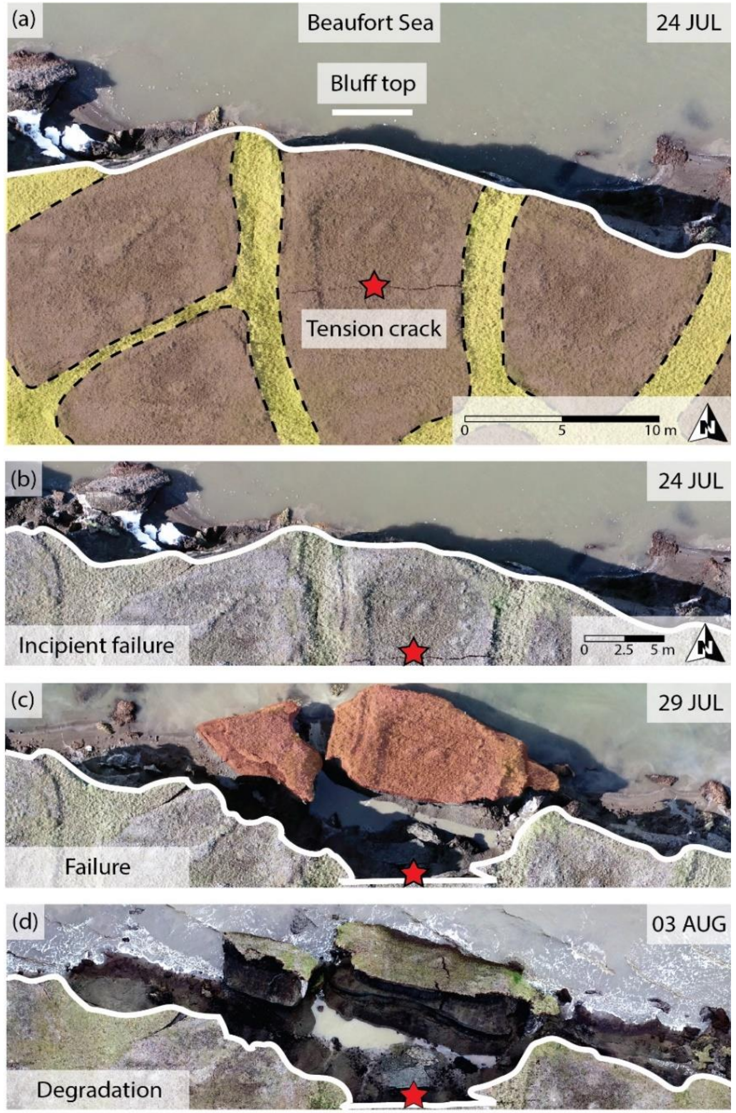
- It has been observed that **failure** can occur along **tension cracks** in ice wedge polygon centers.



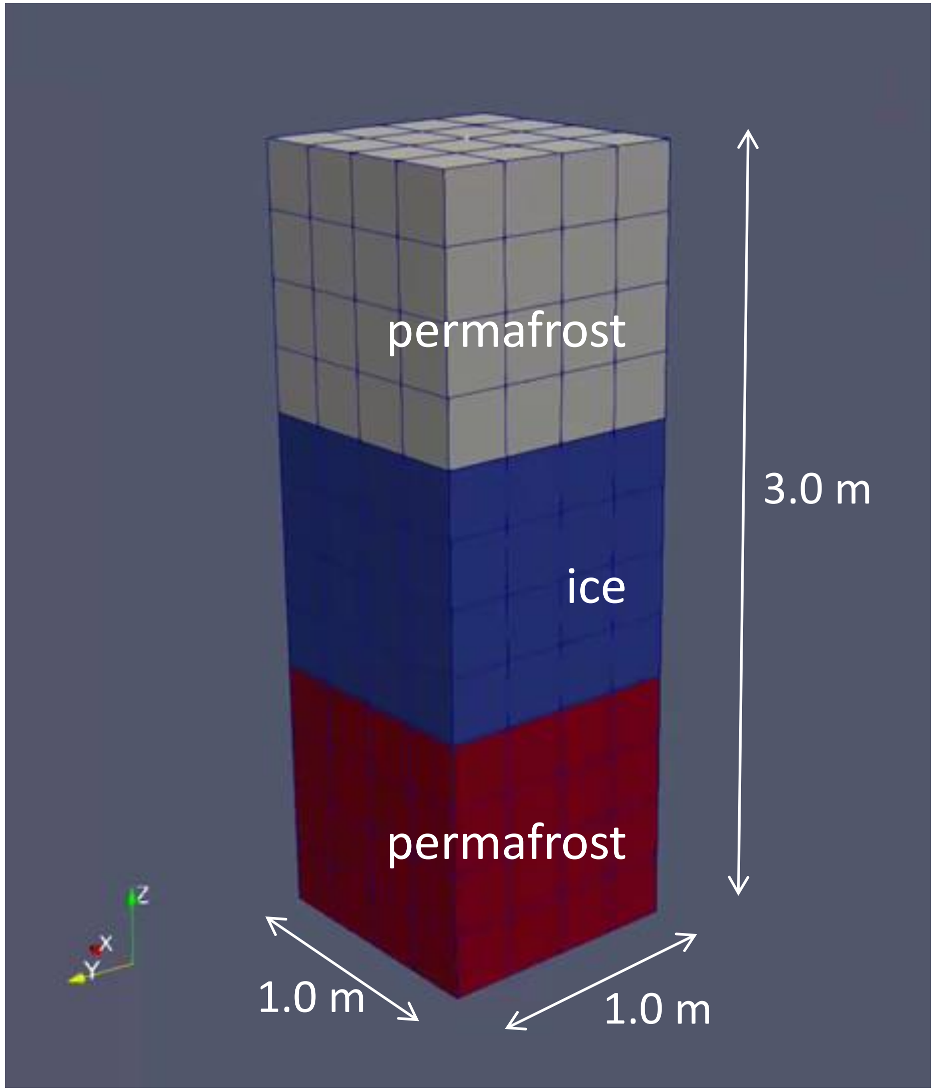

- Simulations suggest **tension cracks** can form within the range of niche depths/heights considered here.

- Even relatively **shallow vertical cracks** can **concentrate strain** within ice-bonded permafrost bluffs.

$F_D$: fracture depth



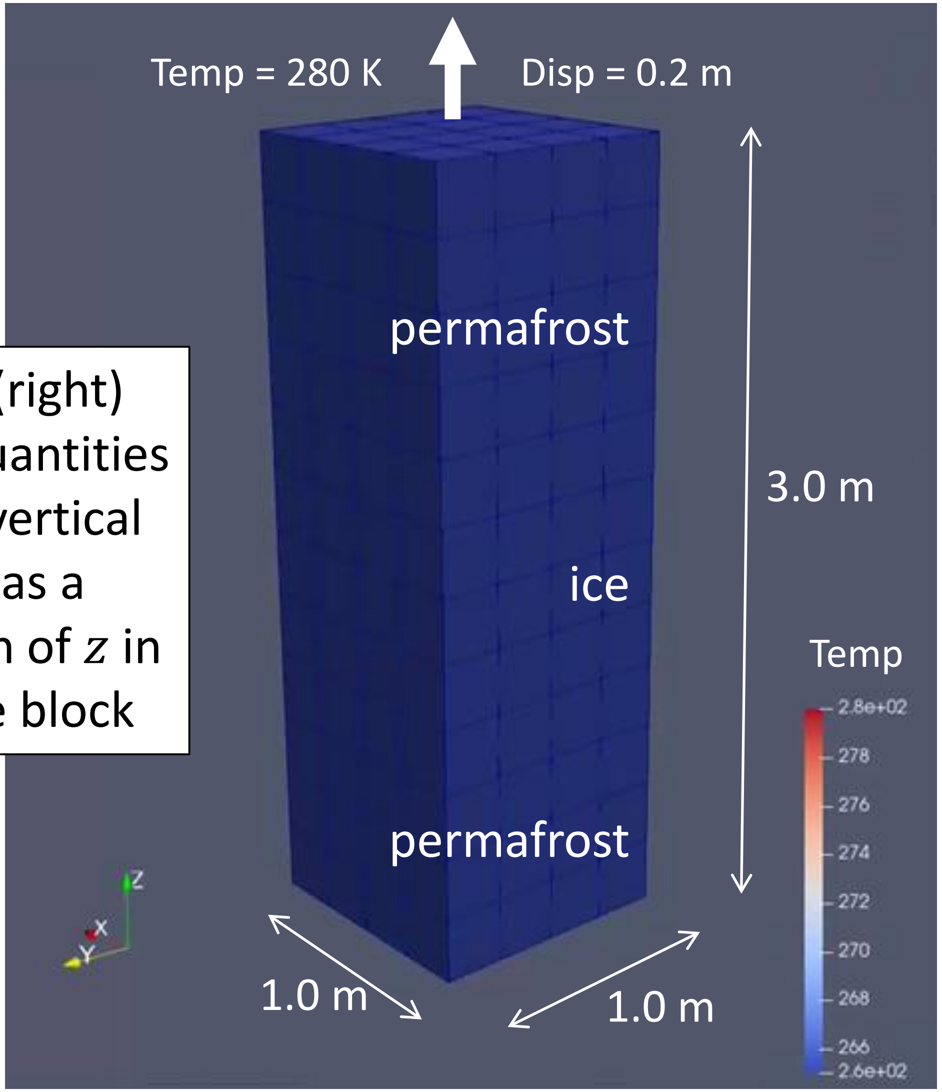
# Thermo-mechanical coupling: cuboid problem



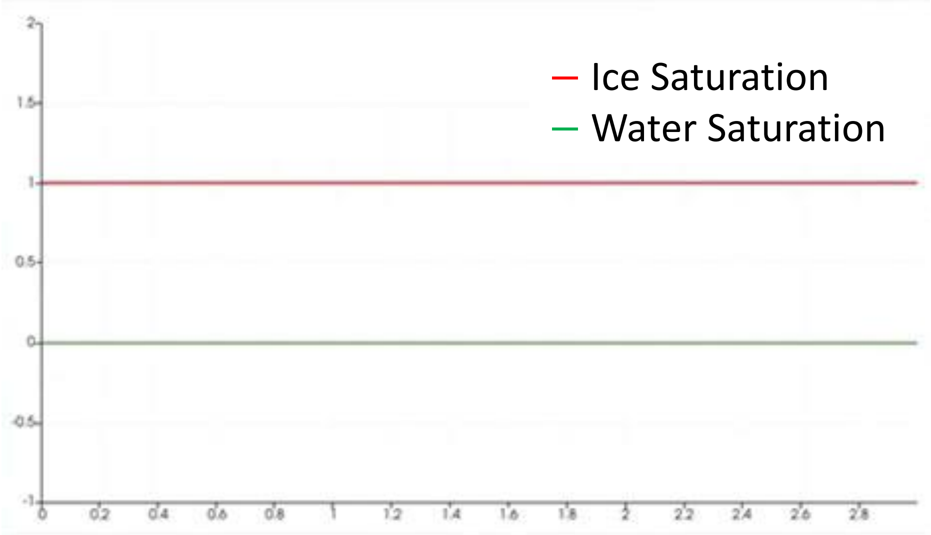

- Cuboid is comprised of block of **ice** material, **wedged** between two blocks of **permafrost** material.
- Cuboid subjected to **simultaneous heating** and **stretching** from the **top**
- Cuboid is **affixed** to the **bottom** and with **symmetry boundary conditions** on the **sides**.
- **Temperature** is initialized to 265K.

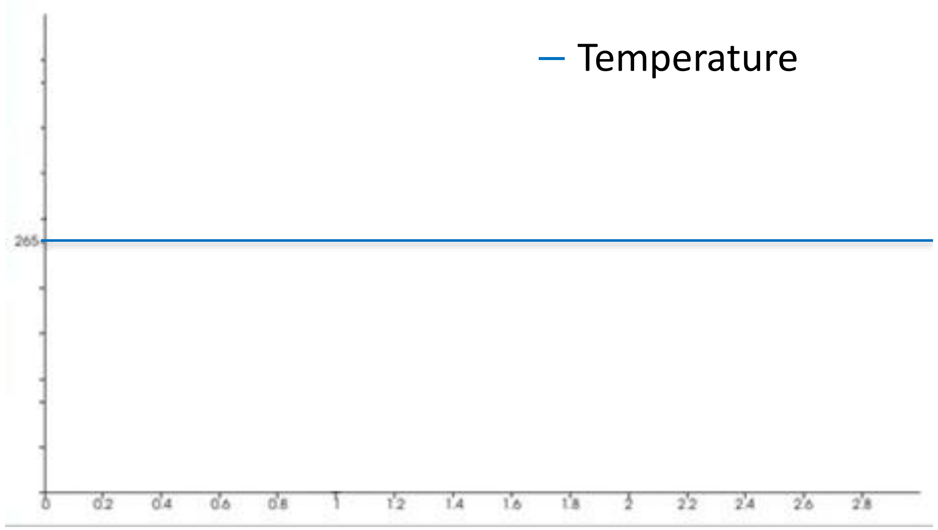
# Thermo-mechanical coupling: cuboid problem

Sandia National Laboratories

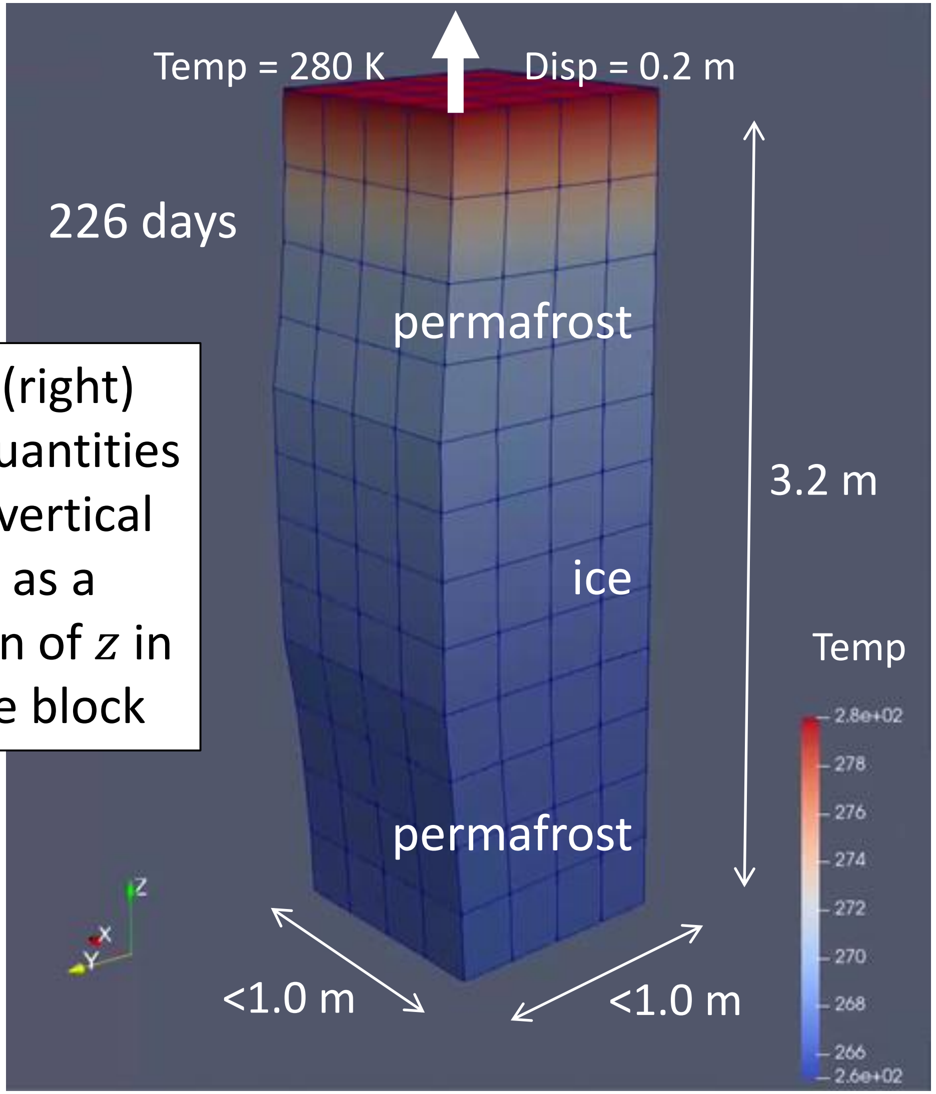



Plots (right) show quantities along vertical line as a function of $z$ in the ice block

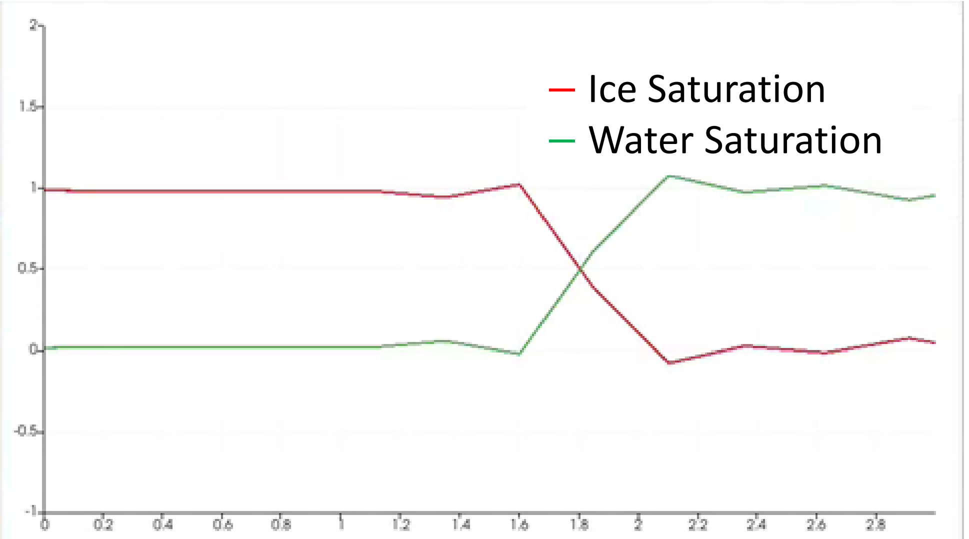


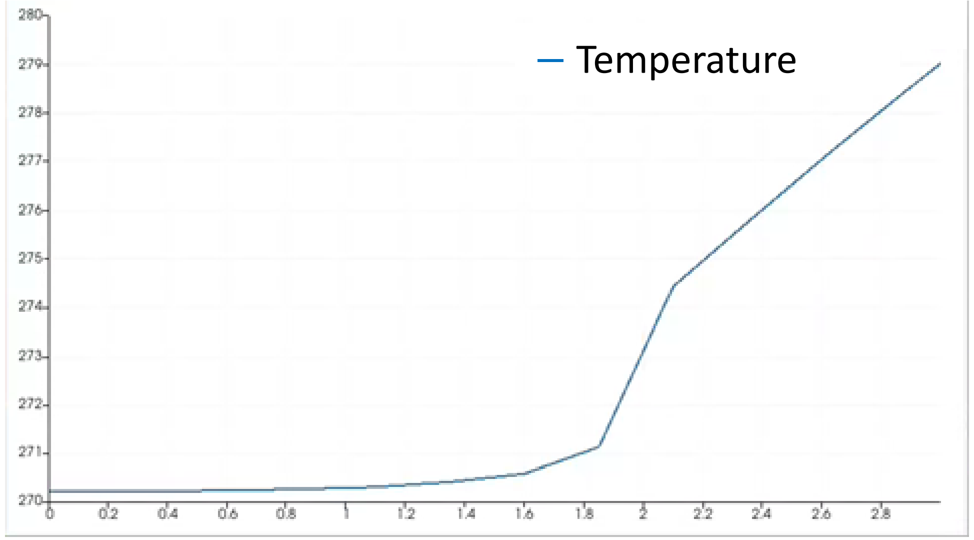



# Thermo-mechanical coupling: cuboid problem




Plots (right) show quantities along vertical line as a function of $z$ in the ice block



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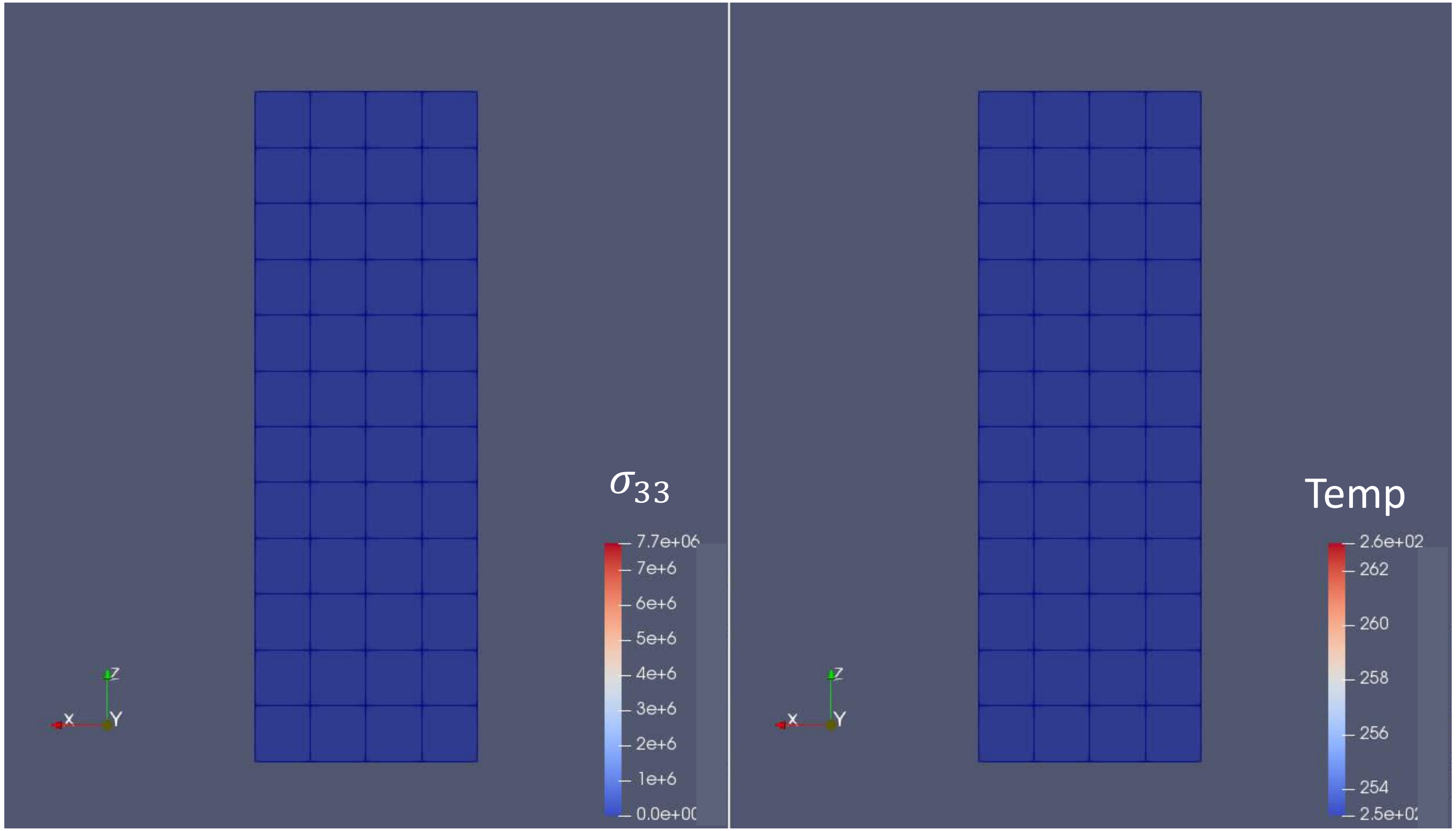
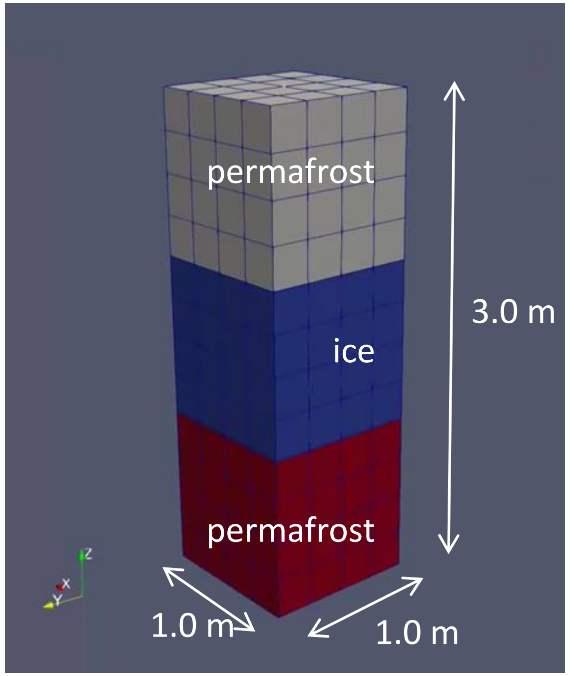


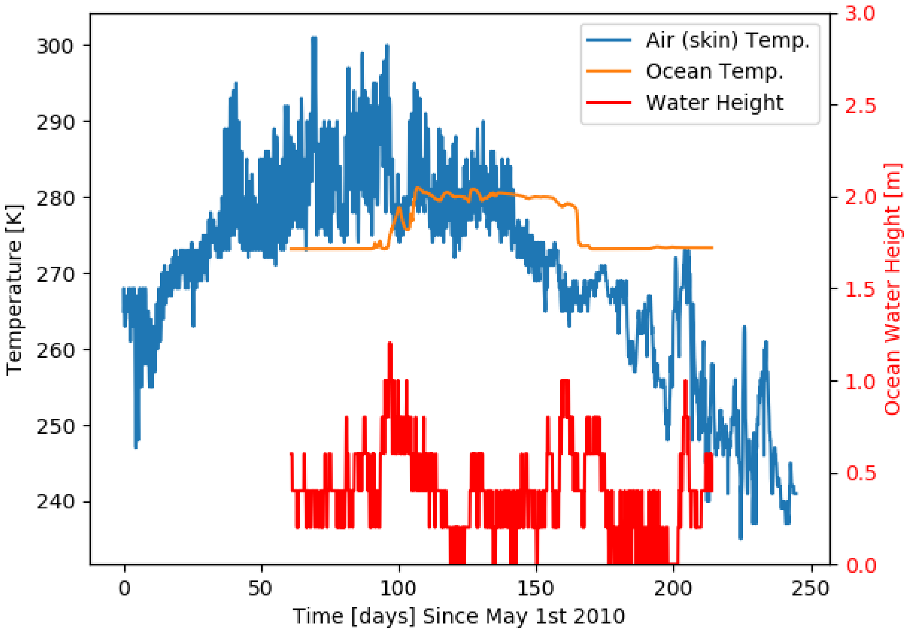

As cuboid is heated and stretched at top, heat propagates down, ***melting ice*** and causing ***failure***.

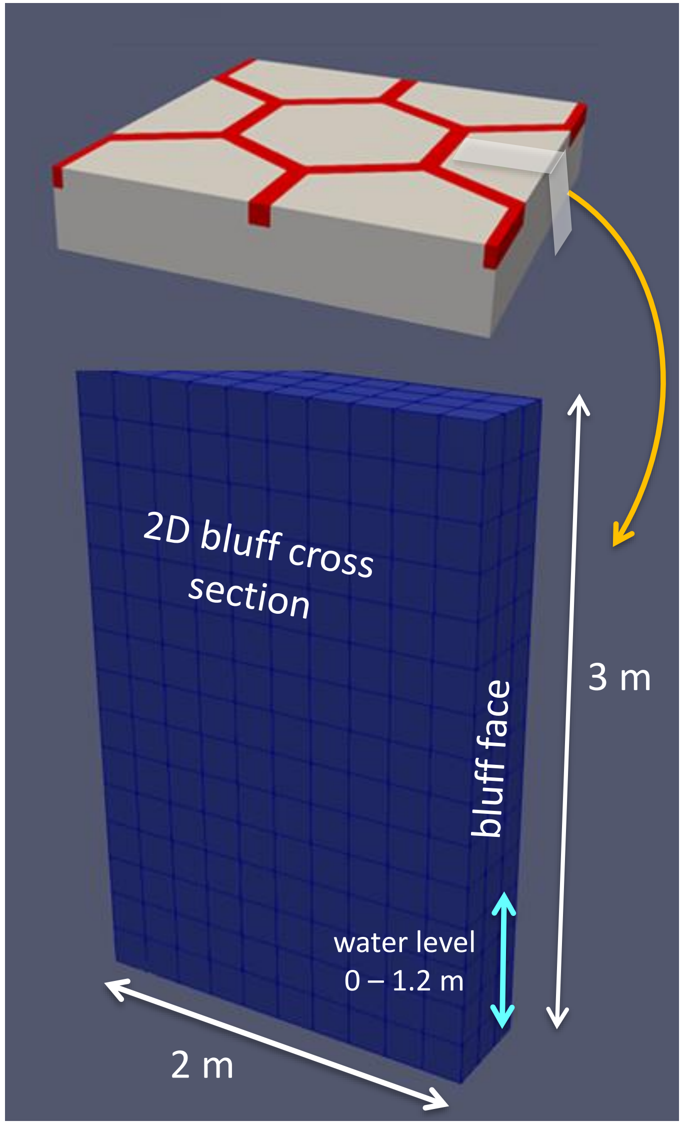
# Thermo-mechanical coupling: 2.5D slice

Sandia National Laboratories

- Computational domain is ***2.5D cross-section*** of archetypal 3D bluff geometry
- ***Time period***: May-Dec. 2011
- ***Air (skin) temperature*** from ASR dataset at 3hr resolution
- ***Ocean temp*** & ***height*** from WW3+SWAN at 20 min resolution
- ***Ice-free period***: July-Oct.
- ***Material properties:*** from laboratory experiments

Our ***initial verification study*** uses real oceanic/ atmospheric BC data but assumes material is ***ice only***.



# Thermo-mechanical coupling: 2.5D slice

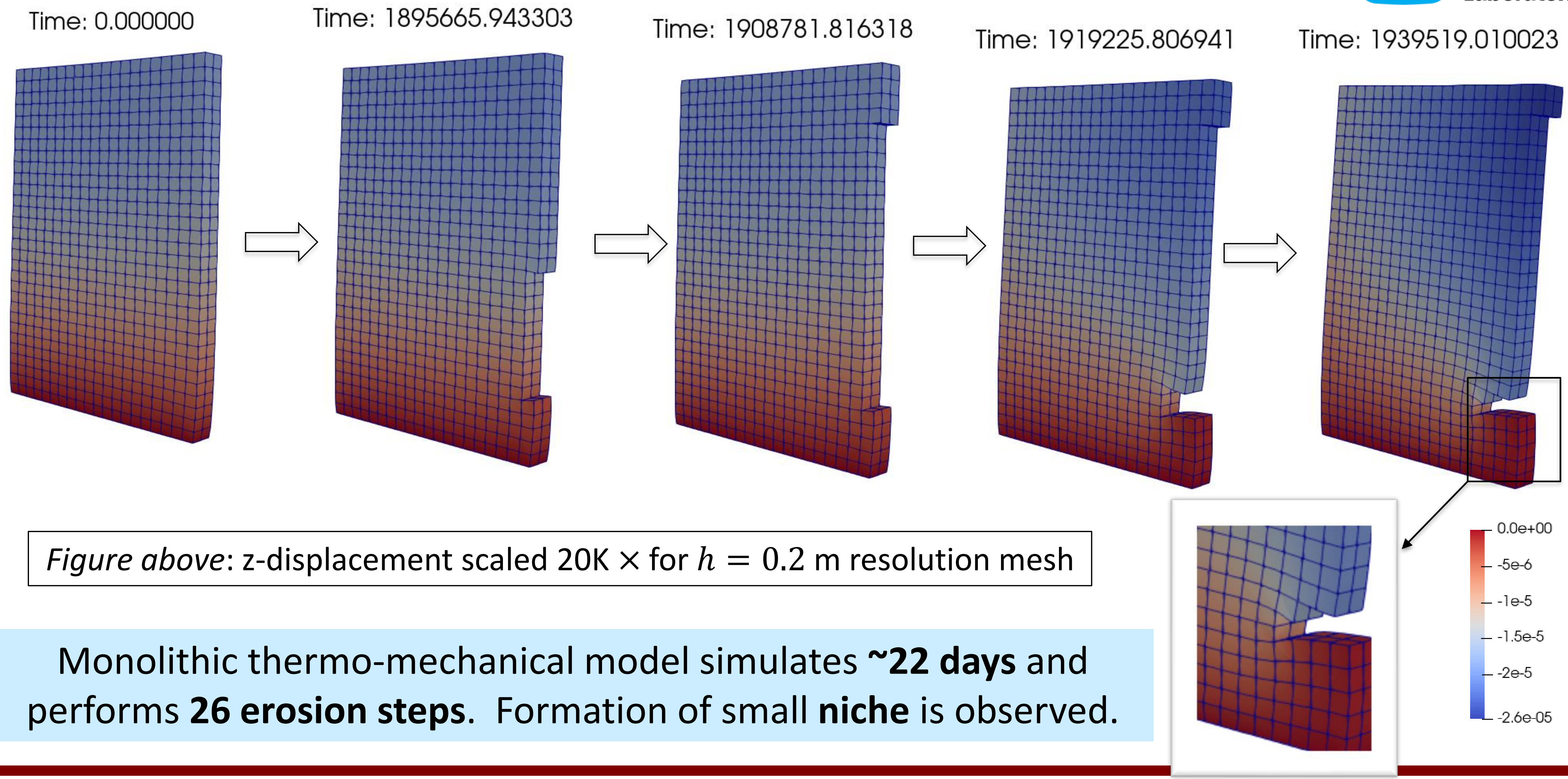



*Figure above*: z-displacement scaled 20K $\times$ for $h = 0.2$ m resolution mesh

Monolithic thermo-mechanical model simulates **~22 days** and performs **26 erosion steps**. Formation of small **niche** is observed.

# Thermo-mechanical coupling: 2.5D slice

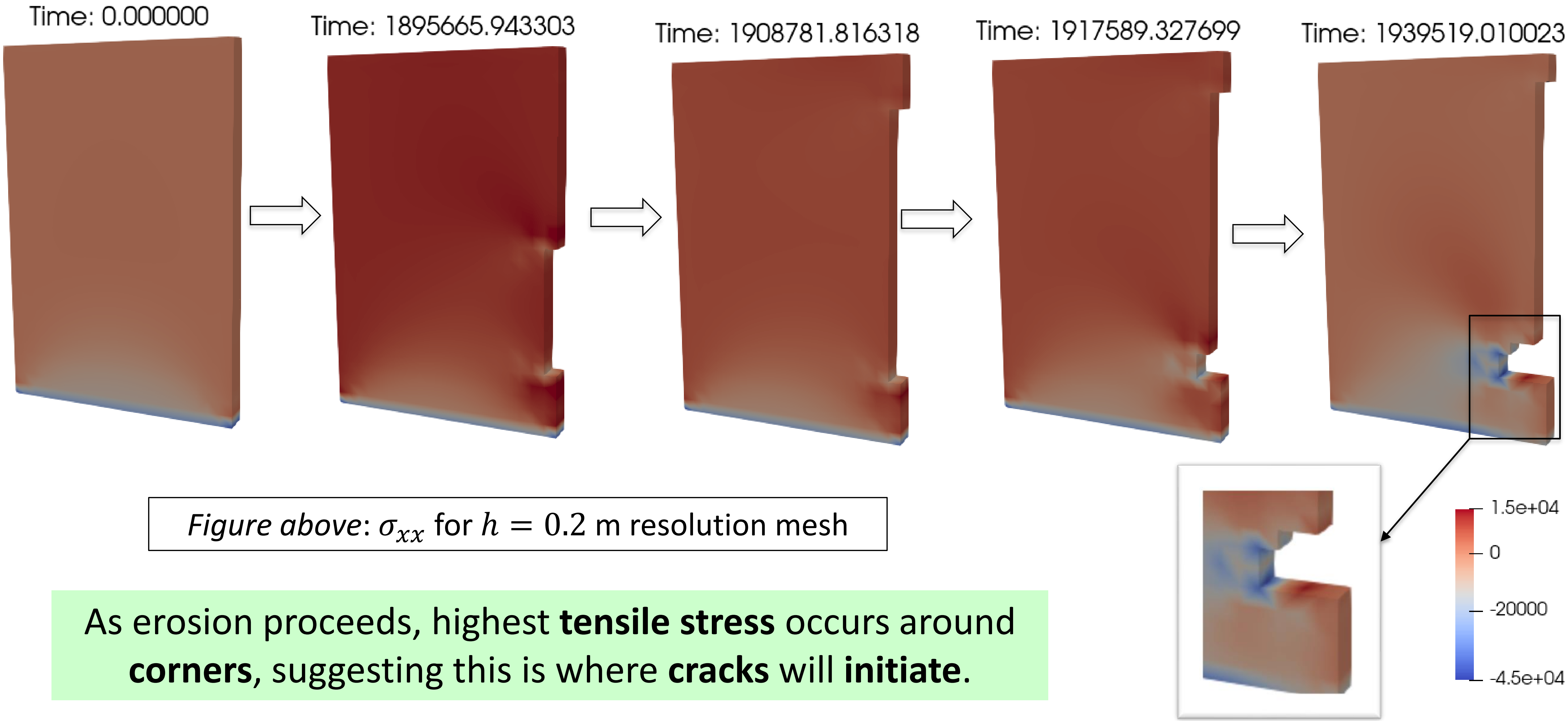



*Figure above*: $\sigma_{xx}$ for $h = 0.2$ m resolution mesh

As erosion proceeds, highest **tensile stress** occurs around **corners**, suggesting this is where **cracks** will **initiate**.

# Thermo-mechanical coupling: 2.5D slice

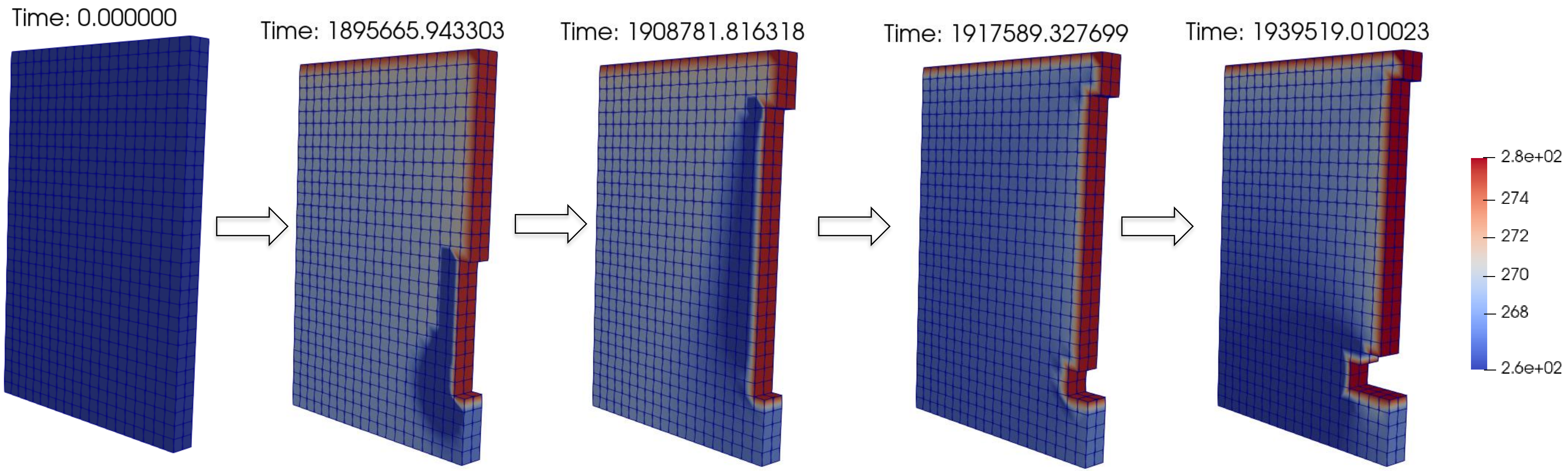



*Figure above*: temperature for $h = 0.2$ m resolution mesh

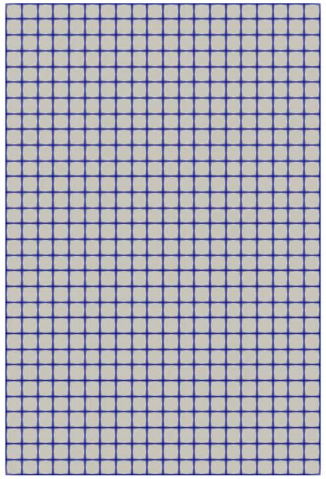
Atmospheric and oceanic **boundary conditions** are driving the **melting** of the ice

# Thermo-mechanical coupling: 2.5D slice

***Some issues to resolve:***

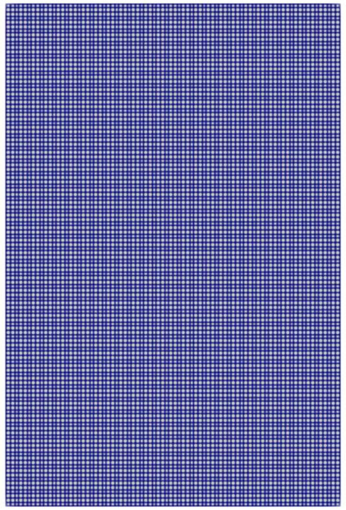
- Results are very ***mesh dependent***.
- For finer mesh resolutions, ***"teeth" patterns*** are observed in the eroded geometry.
  - These do not seem to be physical and need to be understood.
- Regardless of the mesh resolution, simulations ***do not make it past ~22 days***.
  - Nonlinear solver struggles and fails, likely due to large differences in scales between the mechanical and thermal equations.
  - ***Sequential thermo-mechanical*** coupling approach is expected to alleviate this difficulty.

Time: 0.000000



$h = 0.2$ meters

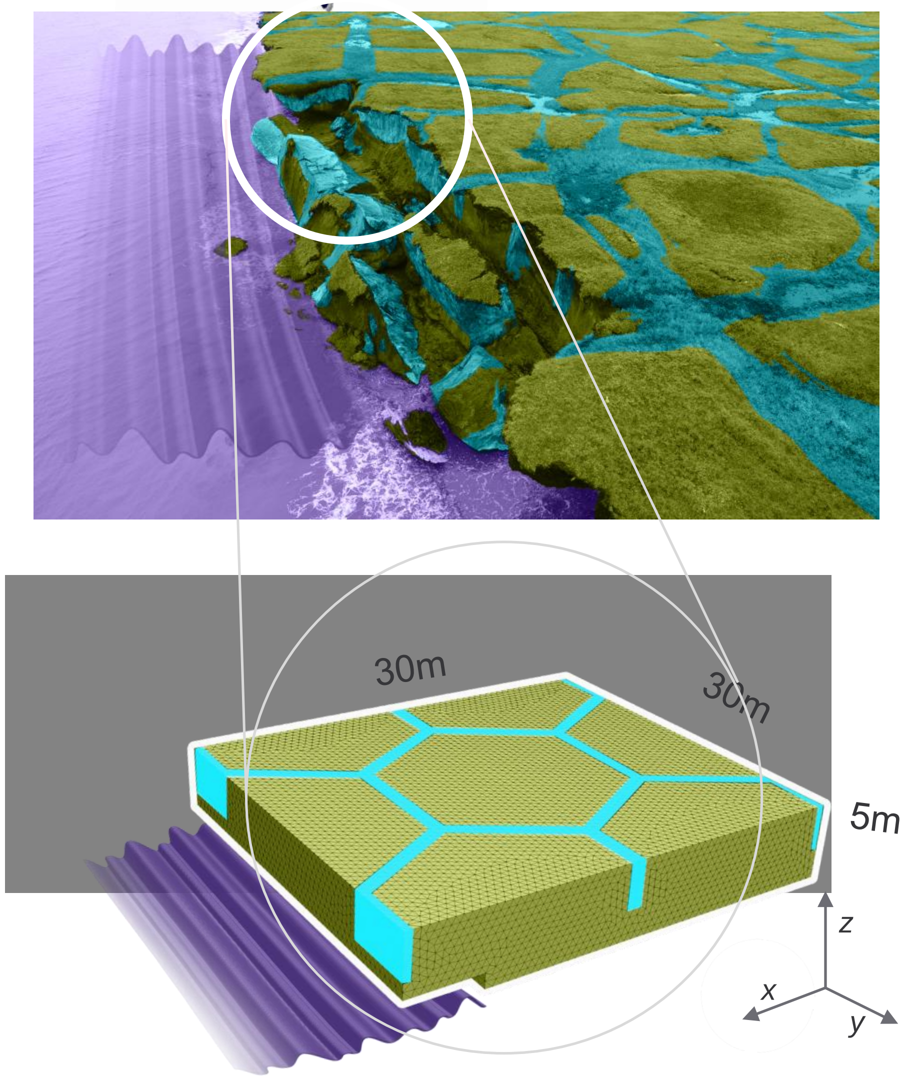
Time: 0.000000



$h = 0.05$ meters

# Summary

- We have developed a ***thermo-mechanical*** coupled FEM model, ***ACE***, that can simulate ***transient niche development*** and ***permafrost erosion*** within Albany.
- The model was ***calibrated*** using data from a series of ***experiments*** on frozen soil samples from Drew Point, Alaska that were performed at SNL's Geomechanics Laboratory to estimate, as well as ***observational data*** collected at the same location.
- The model incorporates ***boundary conditions*** from the ***WW3+SWAN+Delft3D*** wave models and observational data from an August 2019 field campaign at Drew Point, Alaska.



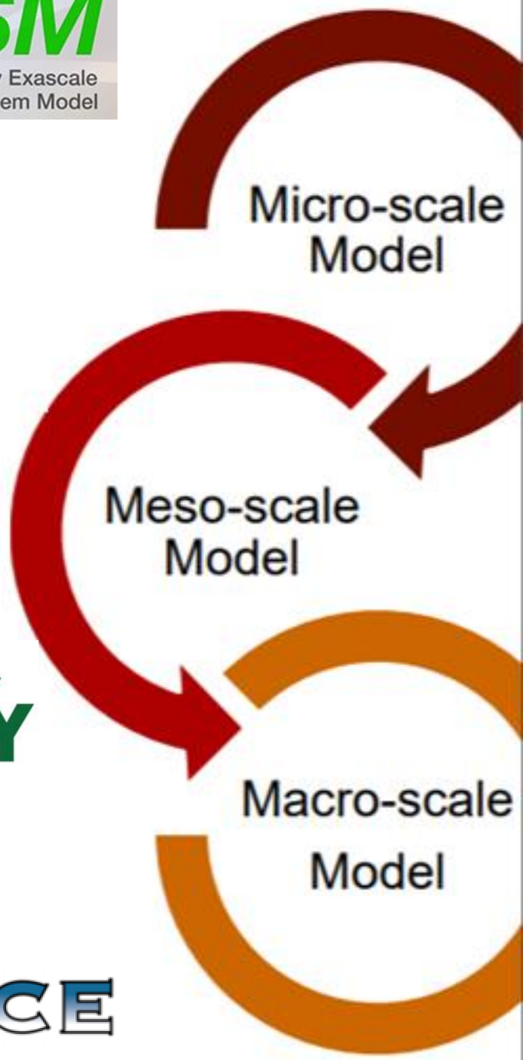
# Ongoing/future work

***Near term:***

- Resolve ***numerical difficulties*** with ACE thermo-mechanical model.
    - ➢ ***Mitigating approach***: sequential coupling between mechanics and thermal equations
- Integrate ***chemical transport*** into ACE model.
- ***Realistic erosion calculations*** using ACE model and Drew Point data.
- ***Tuning/sensitivity studies*** to determine sensitivity ranges at Drew Point.
- ***Validation*** runs to illustrate model skill using FY18-19 data from Drew Point.

***Longer term:***

- Use ACE model to ***understand coastal processes*** in the ***Arctic***.
- Infer ***statistical meso-scale model*** and relevant ***physics-based parameterizations*** from ACE micro-model, towards integration into ESMs.
    - ➢ ACE is member of the newly-funded DOE sponsored ***InteRFACE project**** focused on coastal processes in Arctic.




* Interdisciplinary Research for Arctic Coastal Environments

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[4] J. Brown and O. Ferrians and J. Heginbottom, E. Melnikov. "Circum-Arctic map of permafrost and ground conditions. Boulder, CO: National Snow and Ice Data Center, Digital Media, 1998.

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[8] M. Thomas, A. Mota, B. Jones, C. Choens, J. Frederick, D. Bull. "Bluff geometry and material properties influence stress rates relevant to coastal permafrost block failure". Frontiers in Earth Science 8, 2020.

[9] A. Mota, J. Frederick, D. Bull, I. Tezaur. "Thermo-chemo-mechanical coupling for Arctic Coastal Erosion", in preparation.

# Acknowledgements

## *Research Team*

**SNL**: D. Bull (PI), J. Frederick, A. Mota, C. Choens, I. Tezaur, L. Criscenti

**USGS**: M. Thomas, B. Jones

**UAF**: J. Kasper, E. Brown

**Integral Consulting**: C. Jones, C. Flanary

**U Texas:** J. McClelland, E. Bristol, C. Connolly

# Start of Backup Slides

# Potential impacts

- **3D model** capable of predicting erosion from the material's constitutive relationships capturing all types of **deformation** (**block & denudation**) leading to:
  - **Data-driven** understanding of the characteristics that cause erosion
  - A tool to guide **military** and **civil infrastructure** investments
  - An improved understanding of **coastal food web impacts** and **carbon-climate feedbacks**

- **Redistributed eroded sediment** in the environment enables:
  - Prediction of deposition locations
  - Estimates of fluxes (biogeochemical, toxins, etc.)

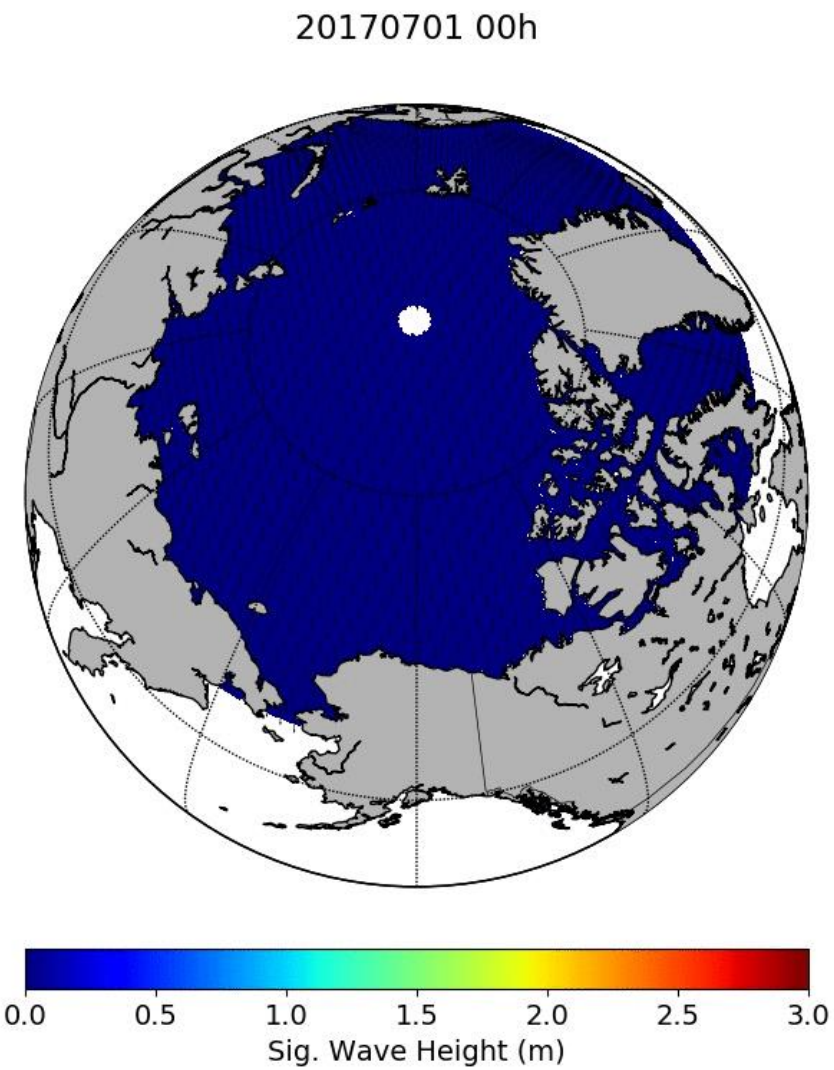
Approach for moving from mechanistic micro-scale to stochastic meso-scale model sets stage for **integration** into **global climate models** built upon parametric analyses of input variables

# Oceanography in Mechanistic Model

**WW3**
Development of wave field in the Arctic to develop nearshore BCs
- surface winds
- ice cover
- temperature (surface and ocean)
- solar radiation
- persistent currents

**SWAN**
Wave set-up conditions 2-way coupled with circulation
- high resolution near shore environment
- capture set-up (storm surge and runup)
- wave energy inclusive of induced current effects

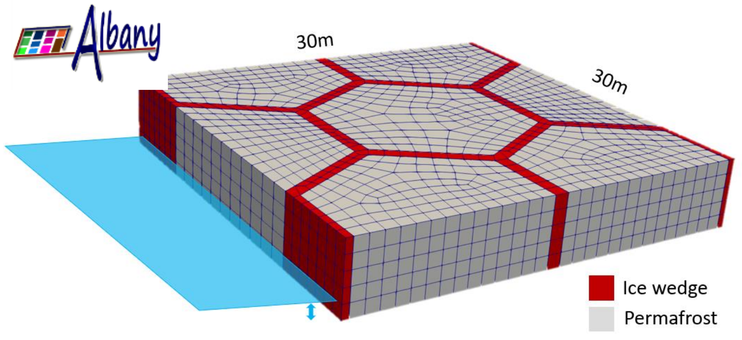
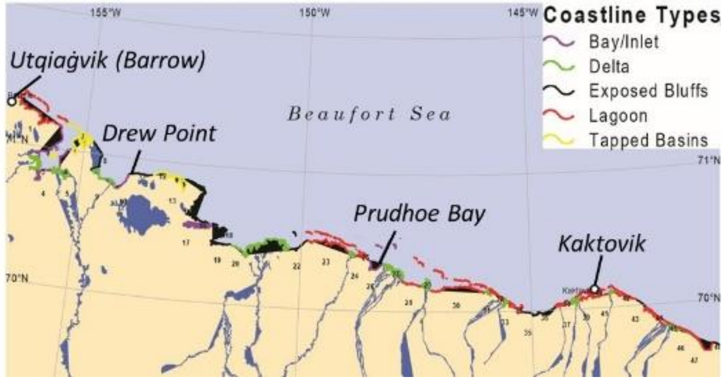
**Delft3D**
Circulation and thermodynamic mixing 2-way coupled with waves
- ability to model mixing of temperature and salinity clines
- capture induced currents in nearshore




WW3 polar stereographic model initially developed by NRL (Erick Rogers) and NOAA (Arun Chawla)

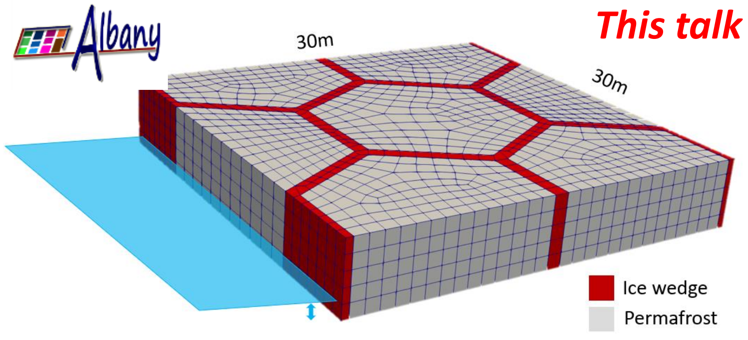
- Potential Key Advances
  - Inclusion of ice coverage for fetch limited wave growth
  - Knowledge of wave energy along broad coastline
  - Set-up determination inclusive of bathymetry and wave energy
  - Ability to accurately predict temperature at bluff face through mixing of clines in the ocean

# Multi-scale approach

| Micro-Scale Model | Meso-Scale Model | Macro-Scale Model |
|---|---|---|
|  |  |  |
| **Micro-Scale Model** | **Meso-Scale Model** | **Macro-Scale Model** |
| 10's of meters & storm duration | 10's of kilometers & monthly duration | 100's of kilometers & annual (+) durations |
| One set of input variables defining the geomorphology and geophysics of the terrestrial model. | A number of micro-scale models that represent the stochastic distributions of input variables along a confined coastline. | A number of meso-scale models that represent the diversity of coastline types (delta, exposed bluffs, lagoons, etc.) along the AK coastline. |

- Working towards a series of fully coupled studies to determine **terrestrial model sensitivities** to:
  - ➢ Height of water on bluff face
  - ➢ Exposure time of bluff face to water
  - ➢ Temperature of water
  - ➢ Salinity of water

# Multi-scale approach




## Micro-Scale Model

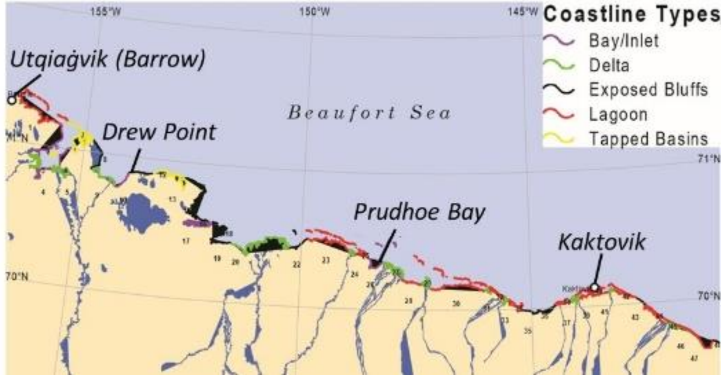
10’s of meters & storm duration

One set of input variables defining the geomorphology and geophysics of the terrestrial model.


## Meso-Scale Model

10’s of kilometers & monthly duration

A number of micro-scale models that represent the stochastic distributions of input variables along a confined coastline.




## Macro-Scale Model

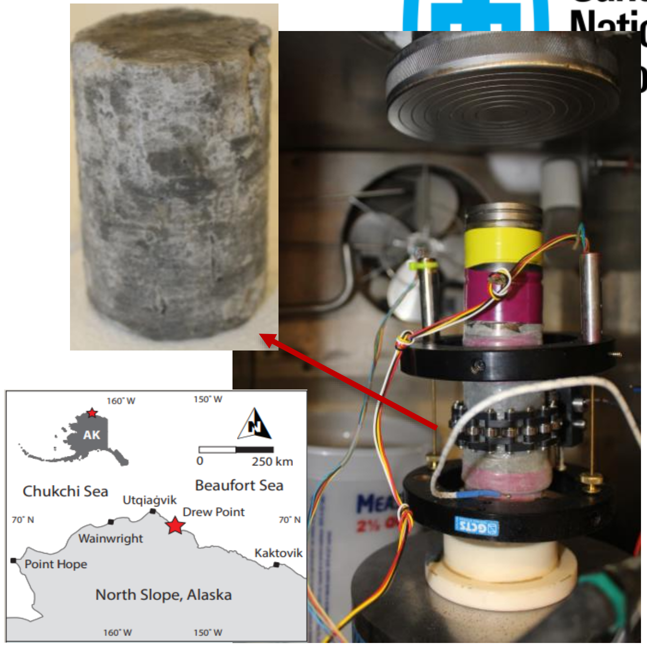
100’s of kilometers & annual (+) durations

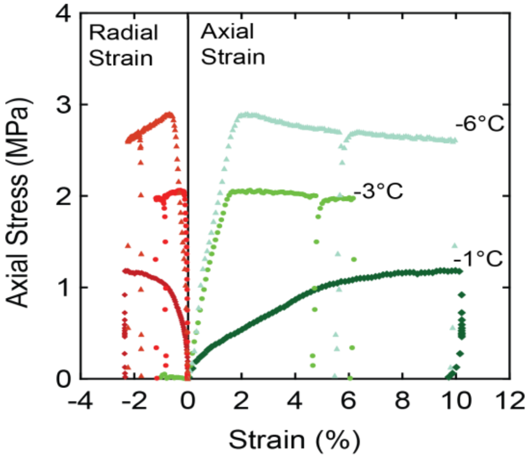
A number of meso-scale models that represent the diversity of coastline types (delta, exposed bluffs, lagoons, etc.) along the AK coastline.

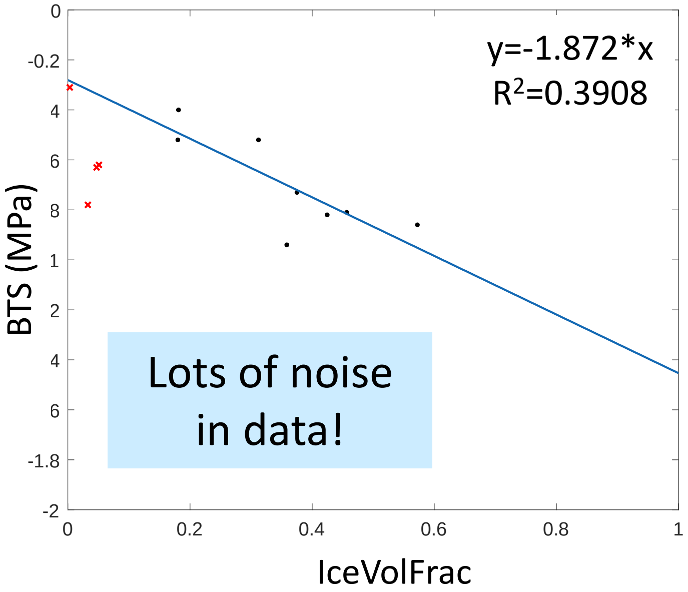
- Working towards a series of fully coupled studies to determine **terrestrial model sensitivities** to:
  - ➢ Height of water on bluff face
  - ➢ Exposure time of bluff face to water
  - ➢ Temperature of water
  - ➢ Salinity of water

# Parameters & inputs

- Permafrost properties depend on ***ice content***, ***unfrozen water content*** and ***frost susceptibility***.
- ***Few mathematical relationships exist*** that describe changes in tensile strength, shear strength and cohesion of ice/permafrost with changes in temperature.
- Series of ***experiments*** (UCS[1], BTS[2], DT[3]) on frozen soil samples at different temps (-6C, -3C, -1C) and ice content from Drew Point, AK were performed at SNL's Geomechanics Laboratory to estimate:
  - ➢ Strength: 1-3 MPa
  - ➢ Young's modulus: 0.01-0.16 GPa
  - ➢ Poisson's ratio: 0.1-0.35
  - ➢ Porosity values: 40-95%

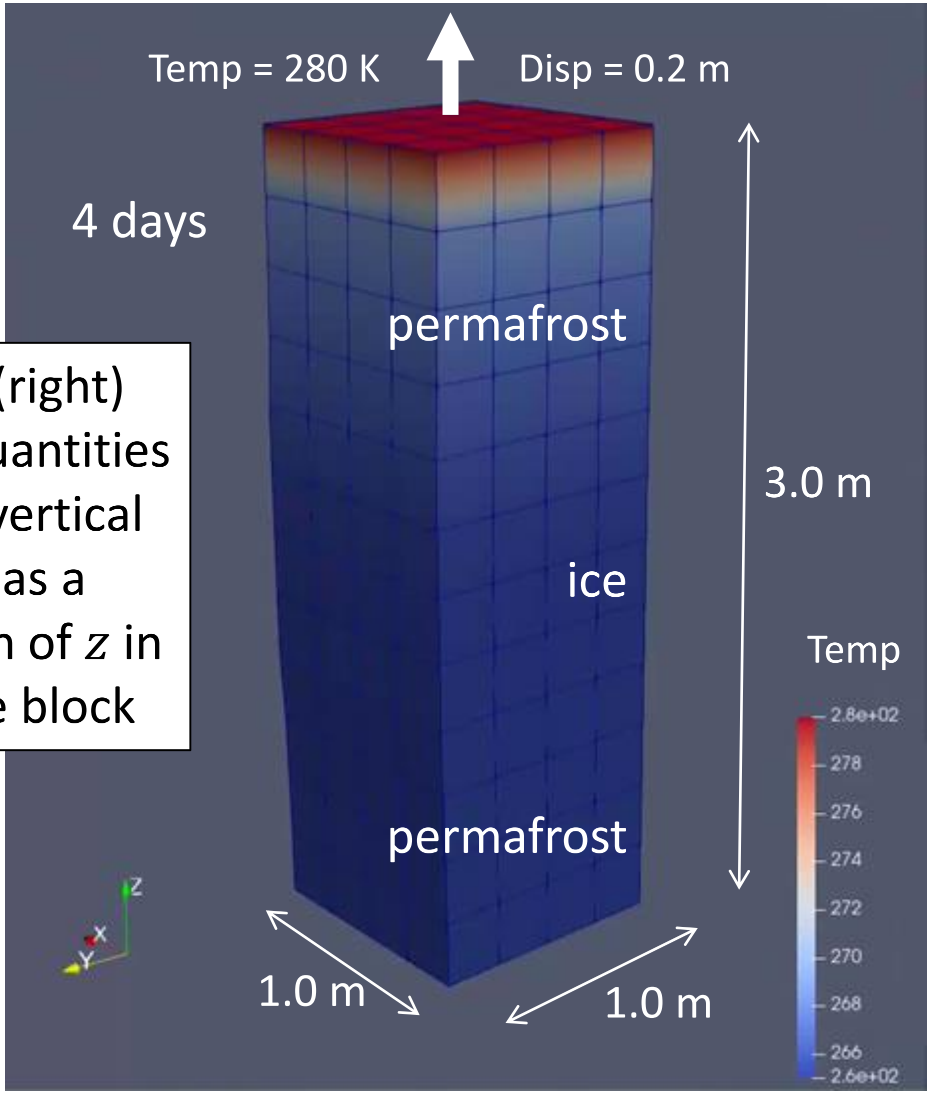


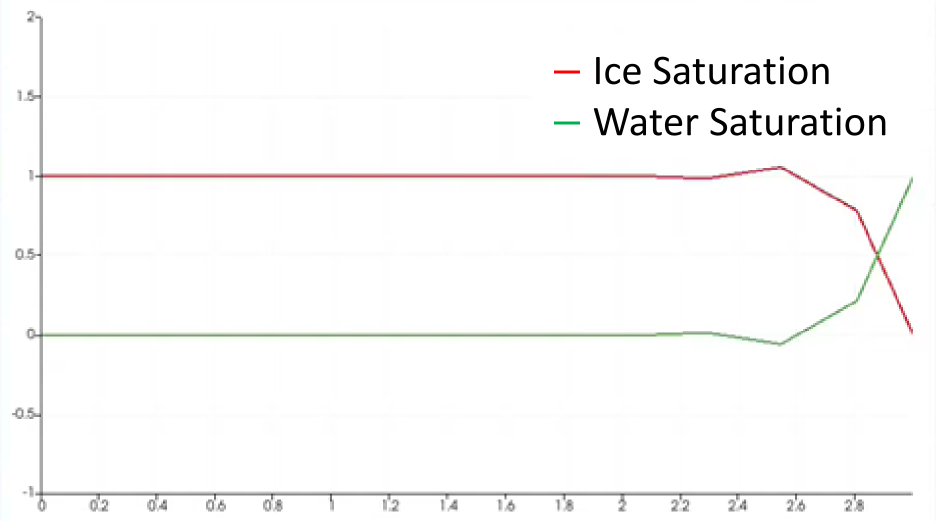



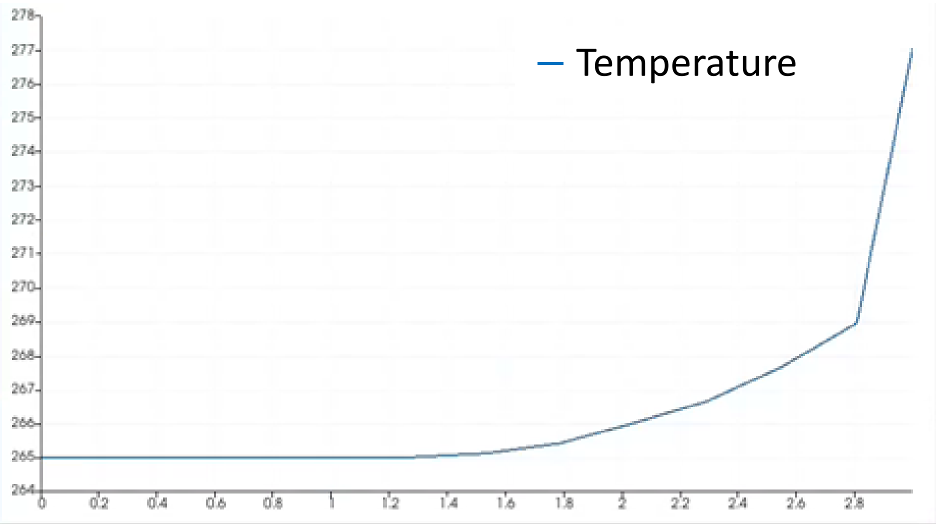

[1] Unconfined compressive test. [2] Brazilian tensile tests. [3] Direct tensile tests.

# Thermo-mechanical coupling: cuboid problem

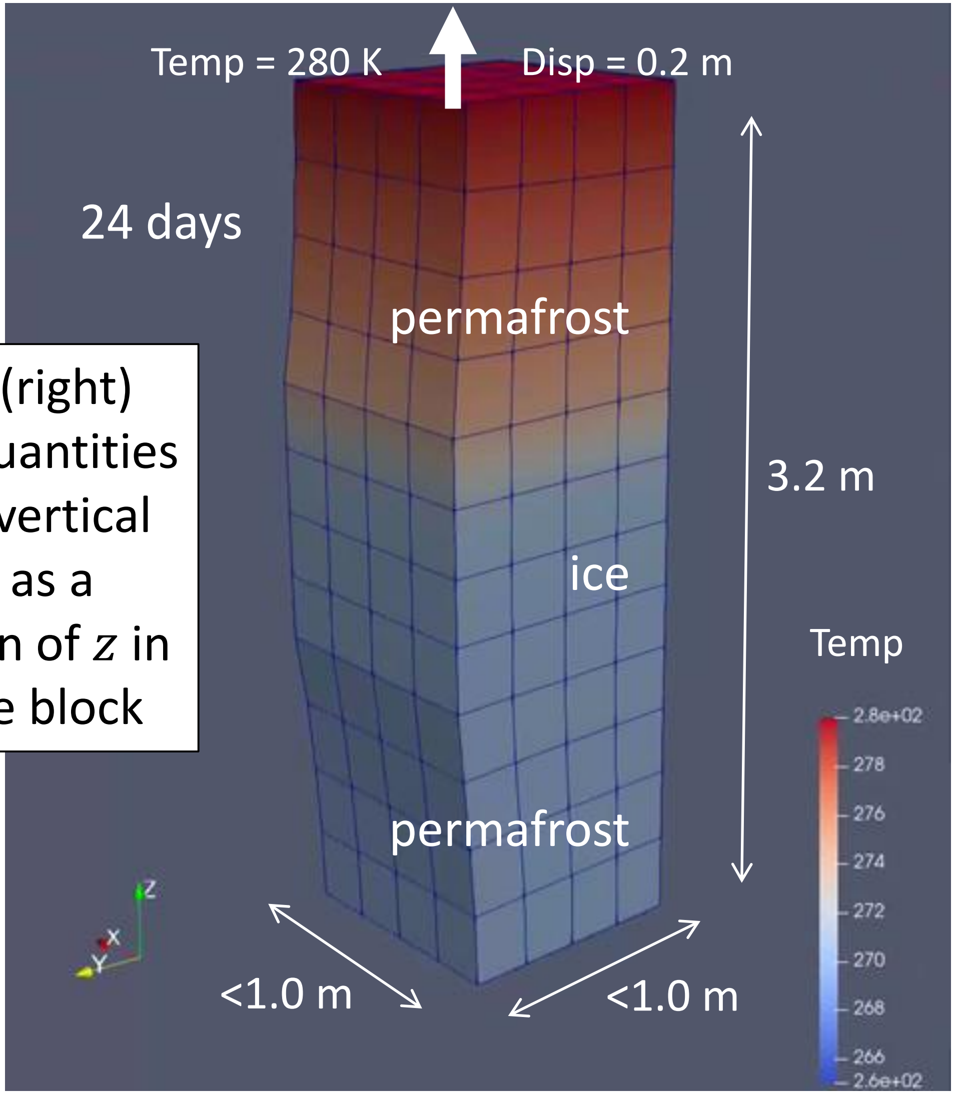



Plots (right) show quantities along vertical line as a function of $z$ in the ice block



# Thermo-mechanical coupling: cuboid problem




Plots (right) show quantities along vertical line as a function of $z$ in the ice block