

# Development of a Tightly Coupled Multi-Physics Numerical Model for an Event-Based Understanding of Arctic Coastal Erosion

**AGU. Arctic Coastal Changes, Hazards, and Risks: Circumpolar Truths and Future Outcomes I. December 9<sup>th</sup> 2019**

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# MOTIVATION

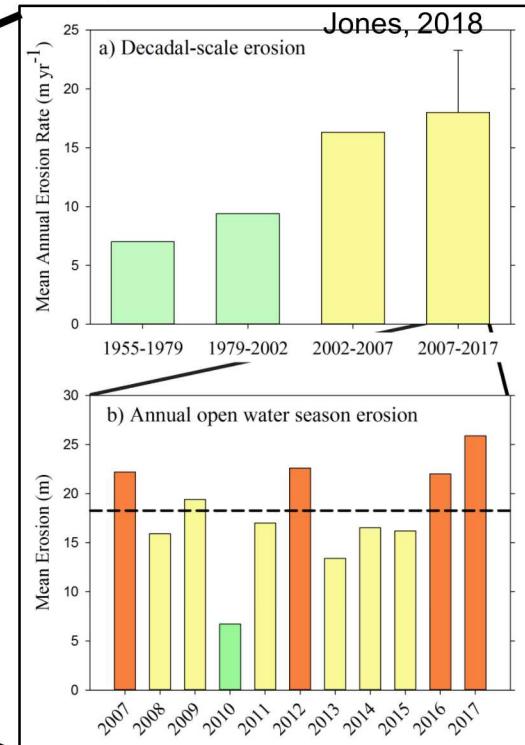
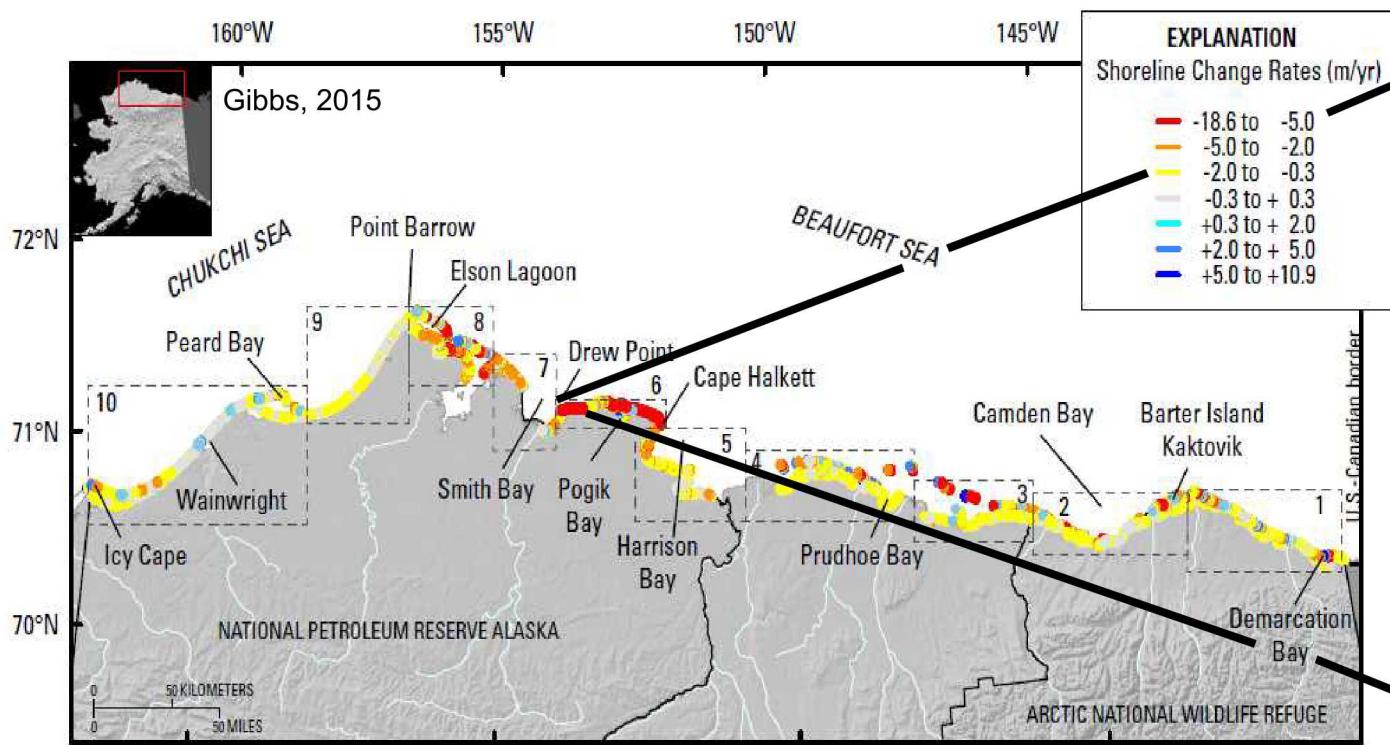
# Problem Statement

The Arctic is warming at 2-3 times the rate of the rest of the US

- 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

There is evidence of areas of accelerating coastal erosion rates

Erosion is threatening: coastal infrastructure, nearshore ecological stability, & global carbon balance



~2 football fields in length in a decade!!

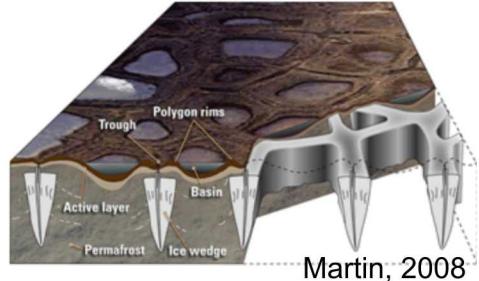
# State of the Technology

Unique erosion process in Arctic:

- Ice acts to bind unconsolidated soils in permafrost
- Melting ice causes failure

Erosion dependent characteristics

- Geomorphology
- Geophysics
- Boundary Conditions

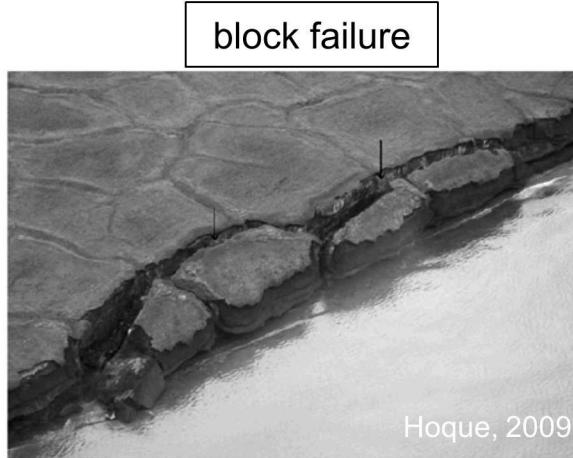


State of the art permafrost erosion modeling

- Trend projection, empirical relationships, 1-D steady state heat flow, ...
- Modeling typically estimates boundary conditions and does not account for geomorphologies or geophysics



retrogressive thaw slumping



block failure

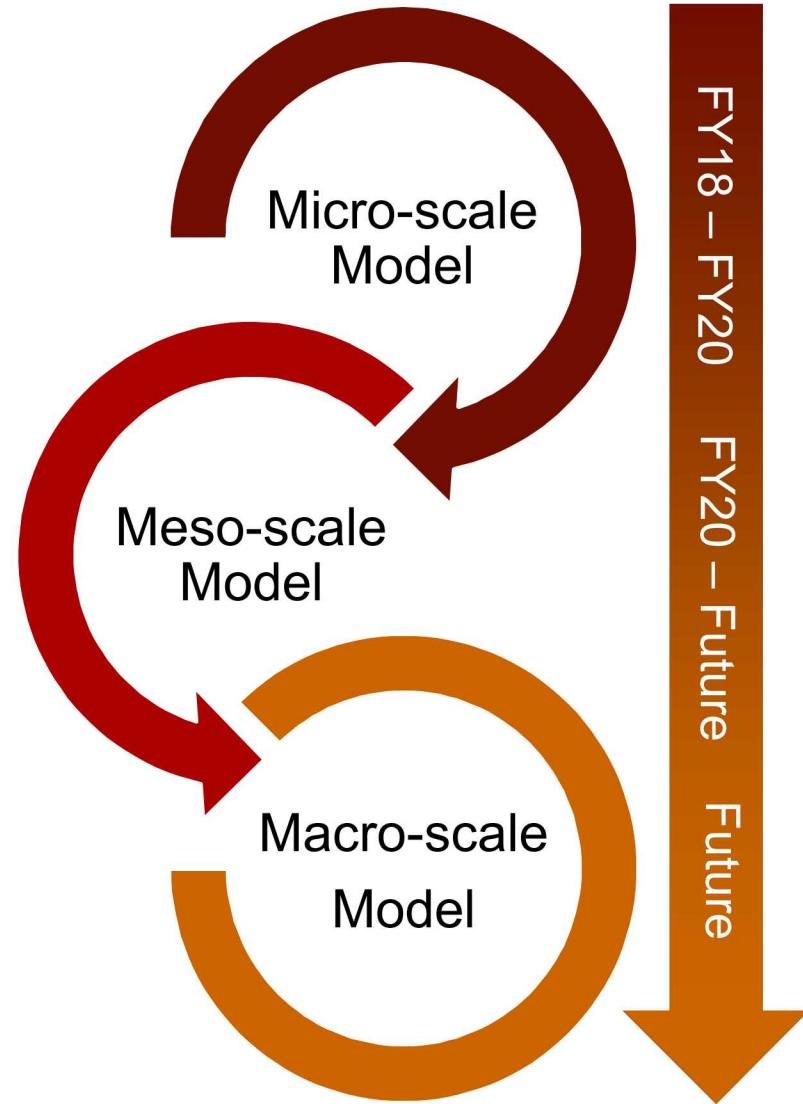


active layer detachment

FY18 – FY20

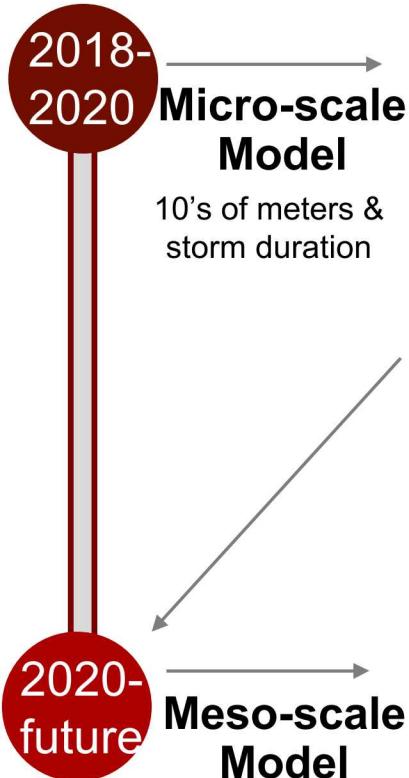
# ARCTIC COASTAL EROSION (ACE) MODELING APPROACH

Project supported by the Laboratory Directed Research and Development program at Sandia National Laboratories.

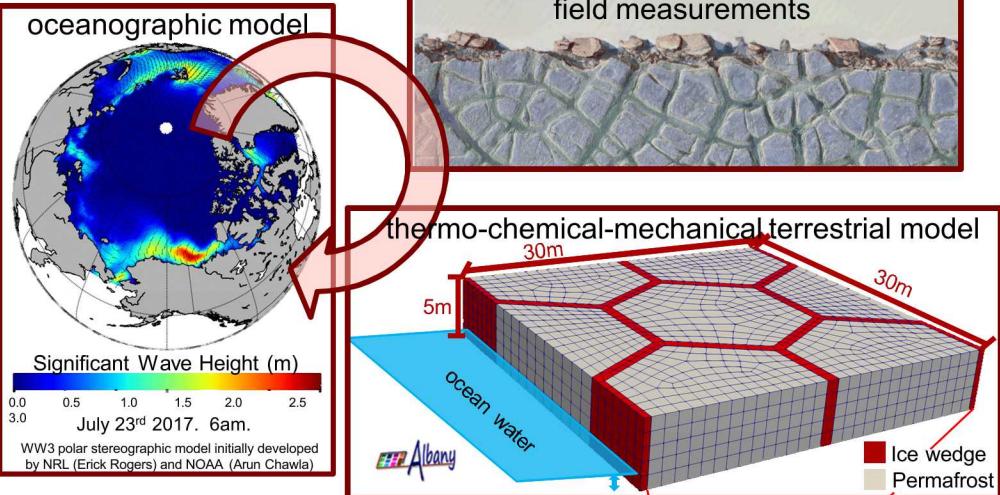


# Proposed Solution

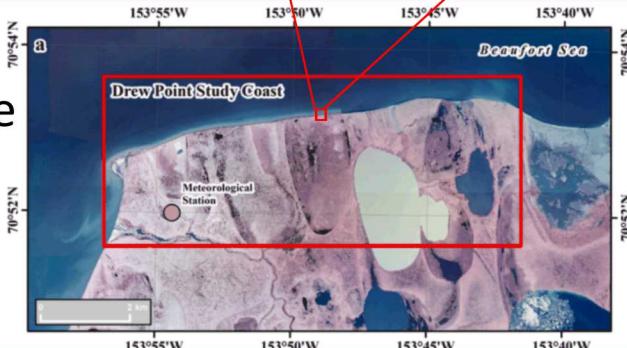
This project will deliver a field-validated predictive model of thermo-chemical-mechanical erosion for the permafrost Arctic coastline.



- Multi-physics finite element terrestrial model coupled with high-fidelity model of water levels along a coastline
  - 3-D thermo-chemo-mechanical constitutive relationships allowing any terrestrial deformation
  - Time-varying boundary conditions of same fidelity and resolution as terrestrial model
  - Eroded sediment and biogeochemical flux tracking

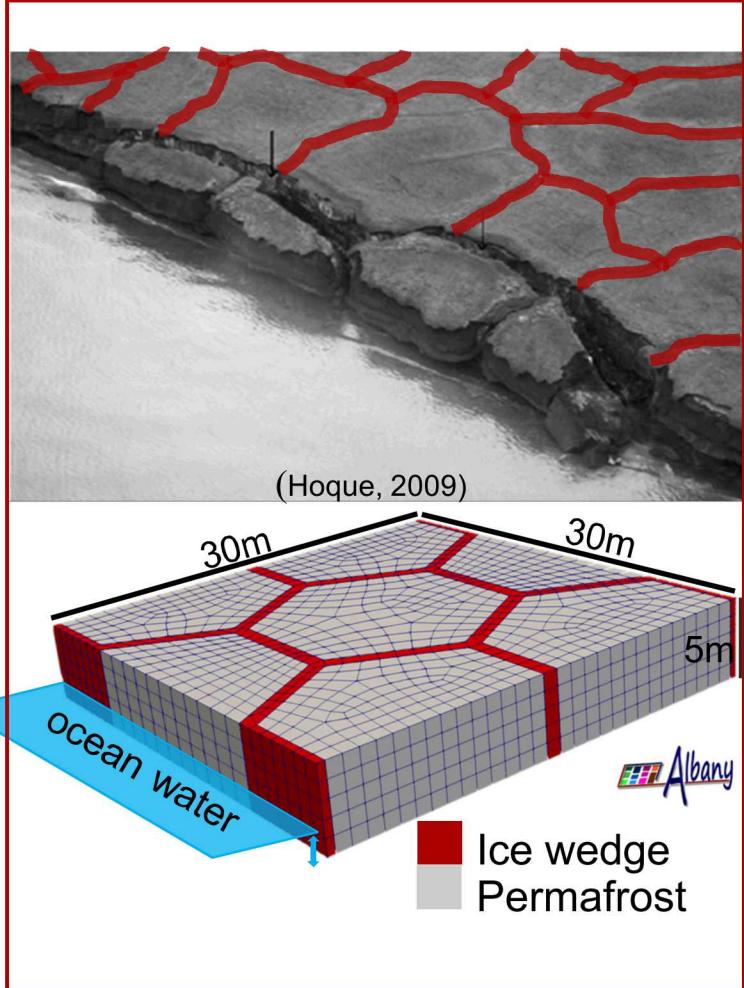


- A weighted combination of micro-scale models representing a stochastic distribution of terrestrial configurations along a coastline
  - Site specific probability distribution functions of geomorphology and geophysics used to weight erosion output
  - Evaluating ocean “exposure metrics” to represent time-varying ocean



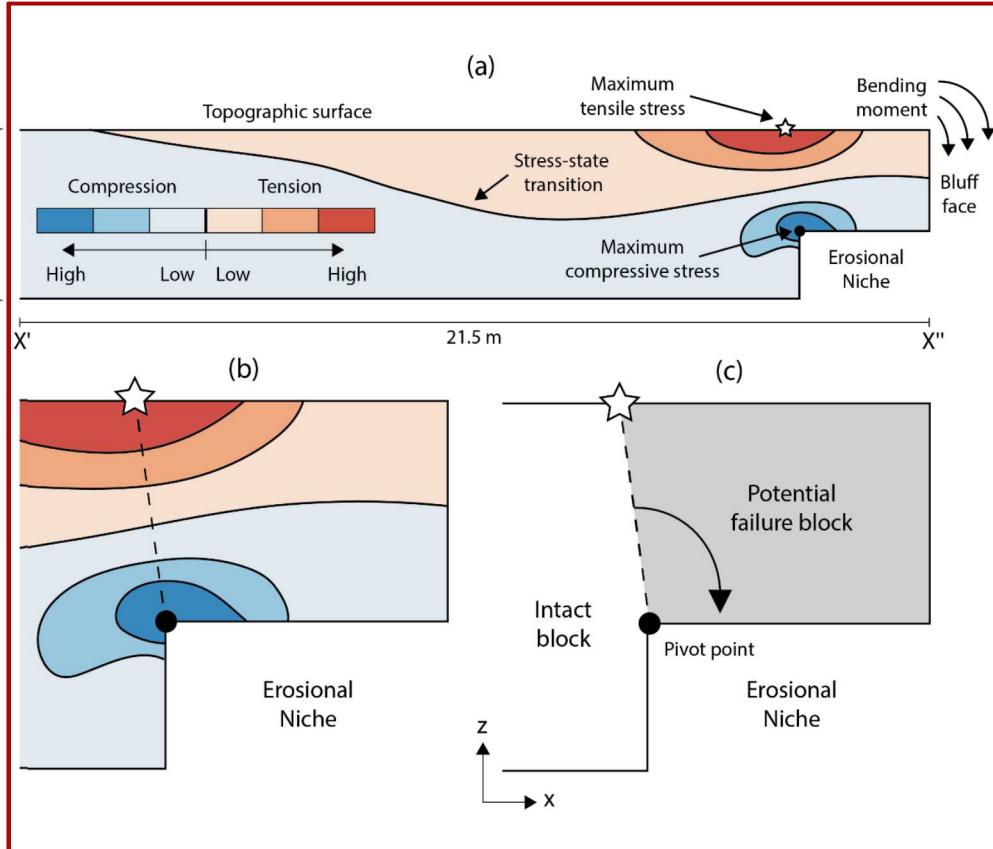
# Focus: Block Failure

## Modeling Interpretation



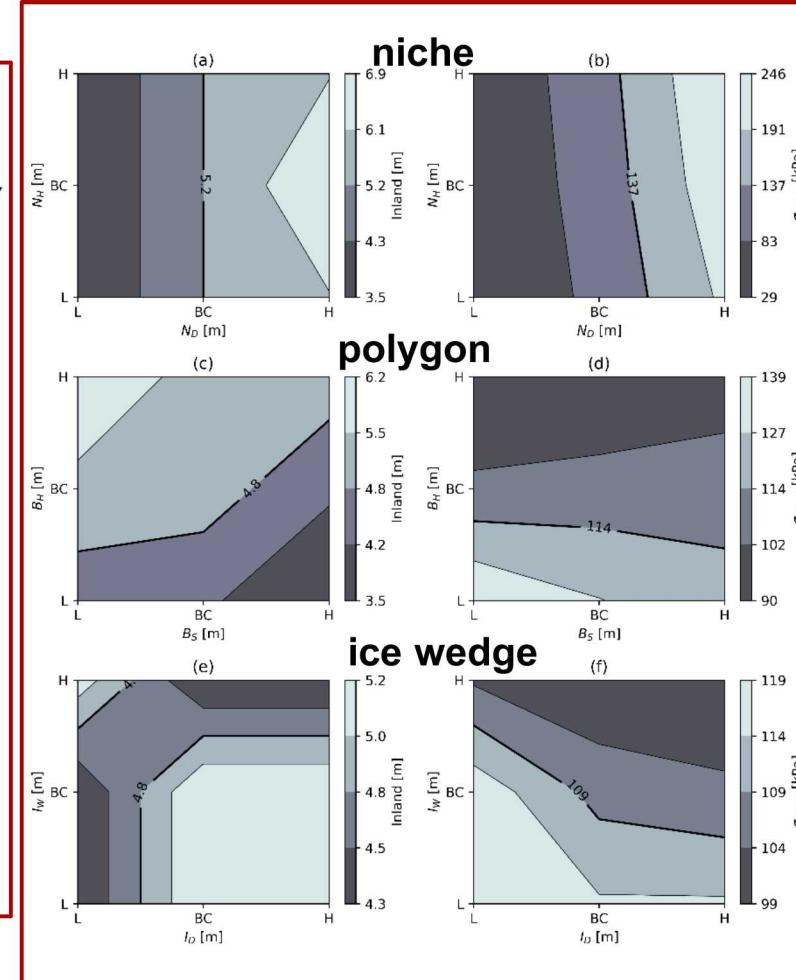
## Conceptual Model of Stress Field

Thomas, submitted



## Geometric Variability

Thomas, submitted



\*Albany is an implicit, unstructured grid, finite element code for the solution and analysis of multiphysics problems developed by SNL and released in public domain

# MICRO-SCALE MODELING

Tightly Coupled Multi-Physics Numerical Model for an Event-Based Understanding of Arctic Coastal Erosion

# Oceanographic Modeling

**WW3** Development of wave field in the Arctic to develop nearshore BC's

- surface winds
- ice cover

**SWAN** Wave set-up conditions 2-way coupled with circulation

- high resolution near shore environment
- wave energy inclusive of induced current effects

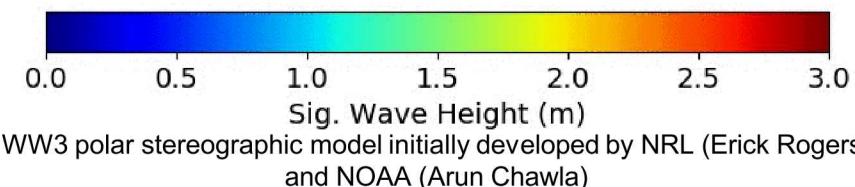
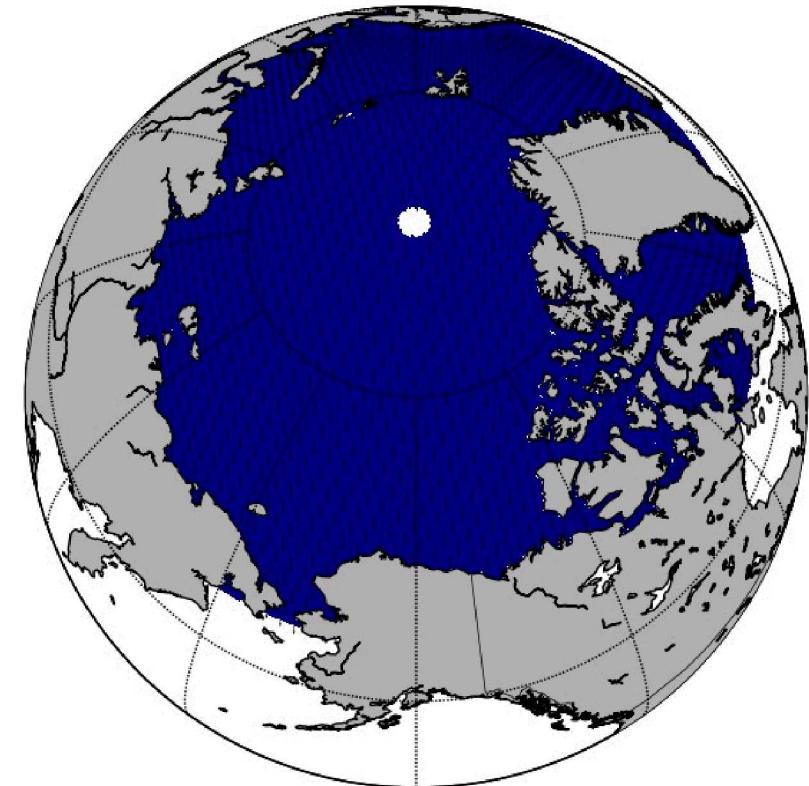
**Delft3D** Circulation and thermal conditions 2-way coupled with waves

- capture induced currents in nearshore
- capture set-up (storm surge and runup)

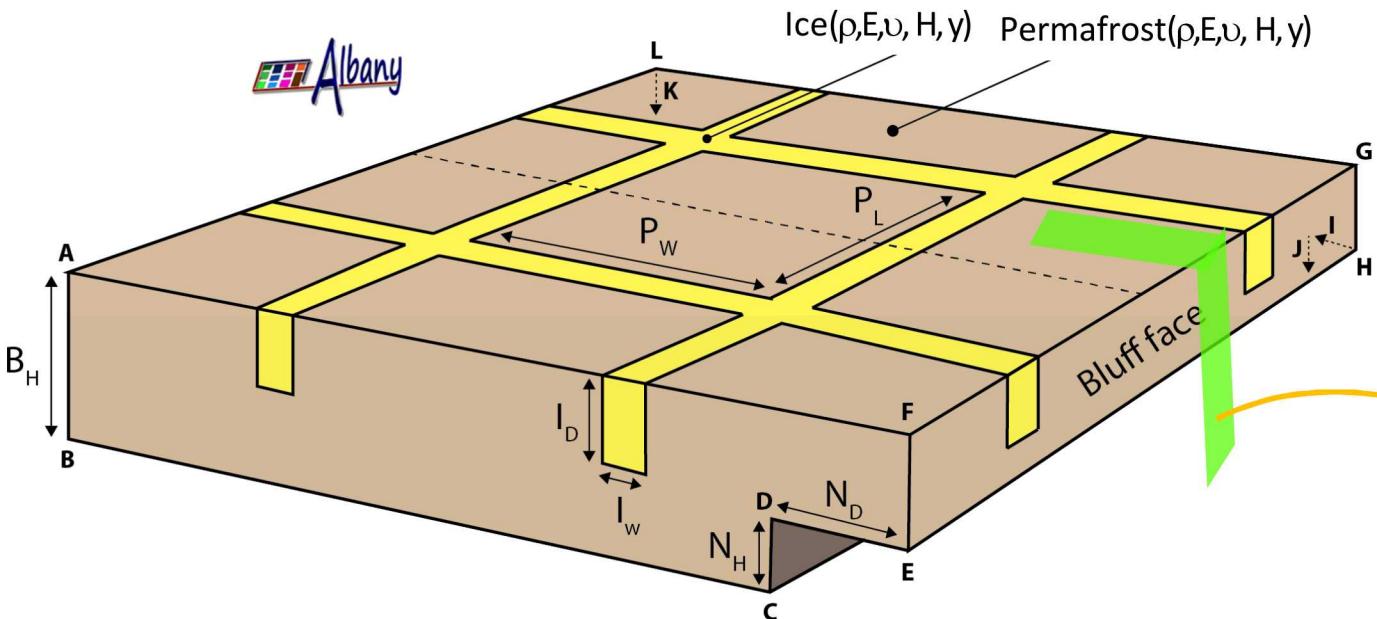
## Key Advances

- High fidelity inputs
  - Oceanographic B.C.'s supplied by ASRv2
  - Inclusion of ice coverage for fetch limited wave growth
  - Local bathymetry verified with measurement
- Knowledge of circum-Arctic wave energy
- Water level derived from combined surge and runup
- Calculating water level, temperature, salinity, and pressure on bluff face from wave environment

20170701 00h  
Flanary, in preparation

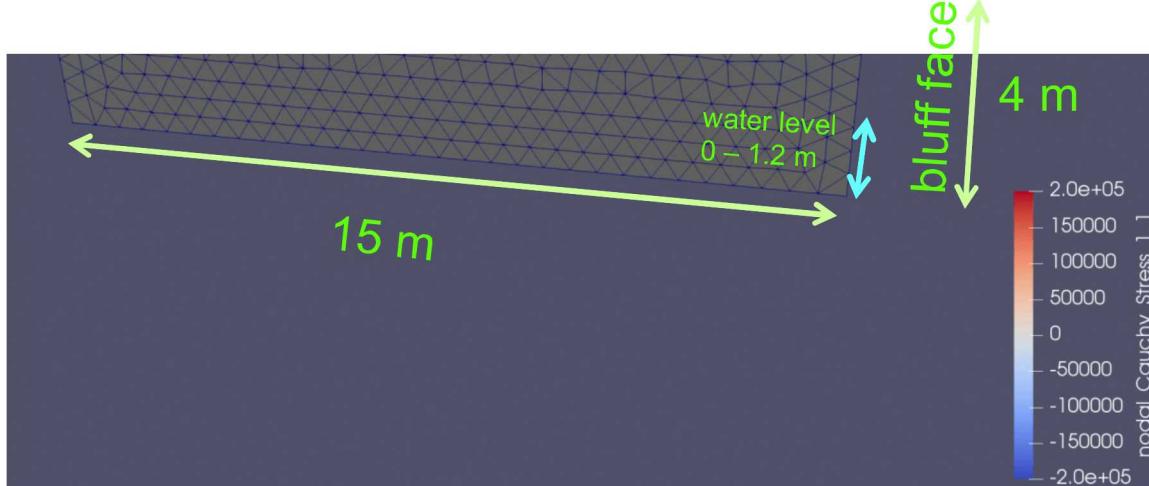


# Terrestrial Modeling



Frederick & Mota, in preparation

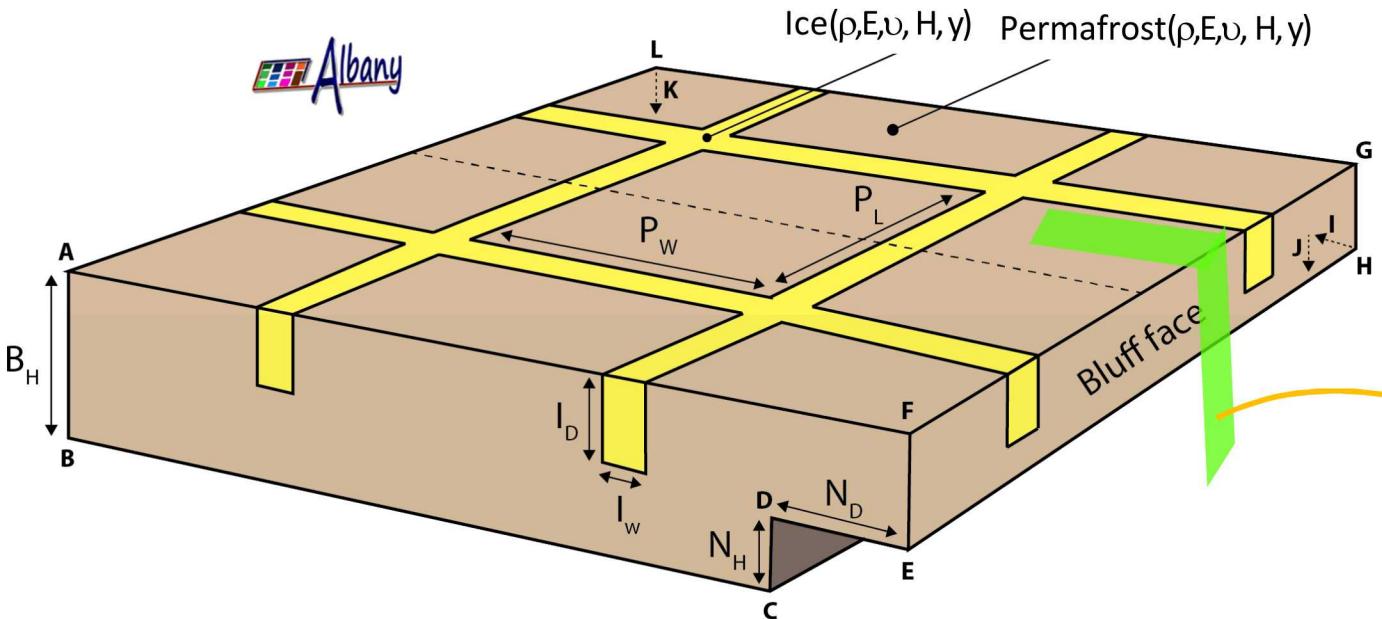
2D bluff cross section of stress



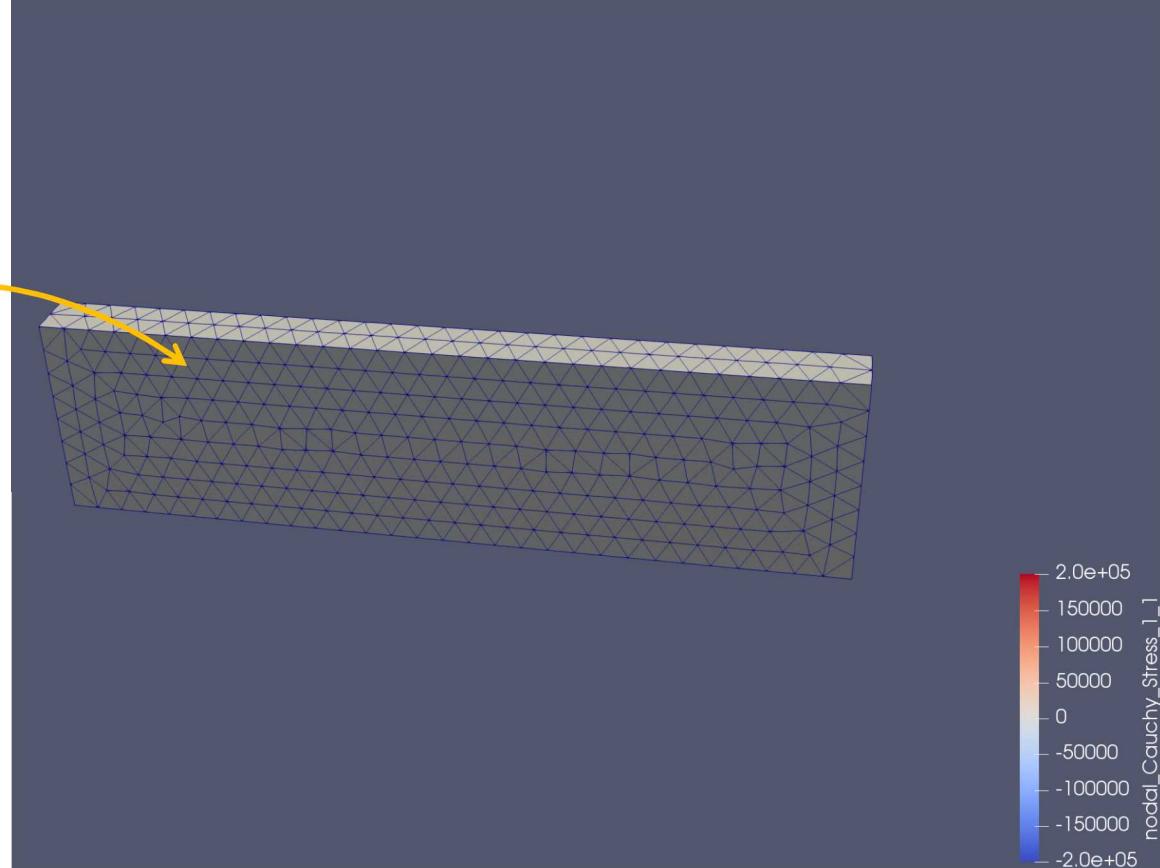
## Key Advances

- 3-D unsteady thermal flow and chemical characteristics
- Tightly coupled strength and thermo-chemical states
- Failure modes develop from constitutive relationships in Finite Element Model (no empirical relationships!)
- Material is dynamically removed as failure strength surpassed

# Terrestrial Modeling



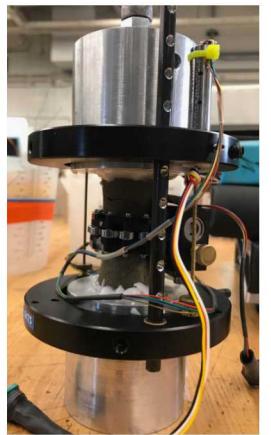
Frederick & Mota, in preparation



## Key Advances

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# Coupled Thermal-Mechanical Response

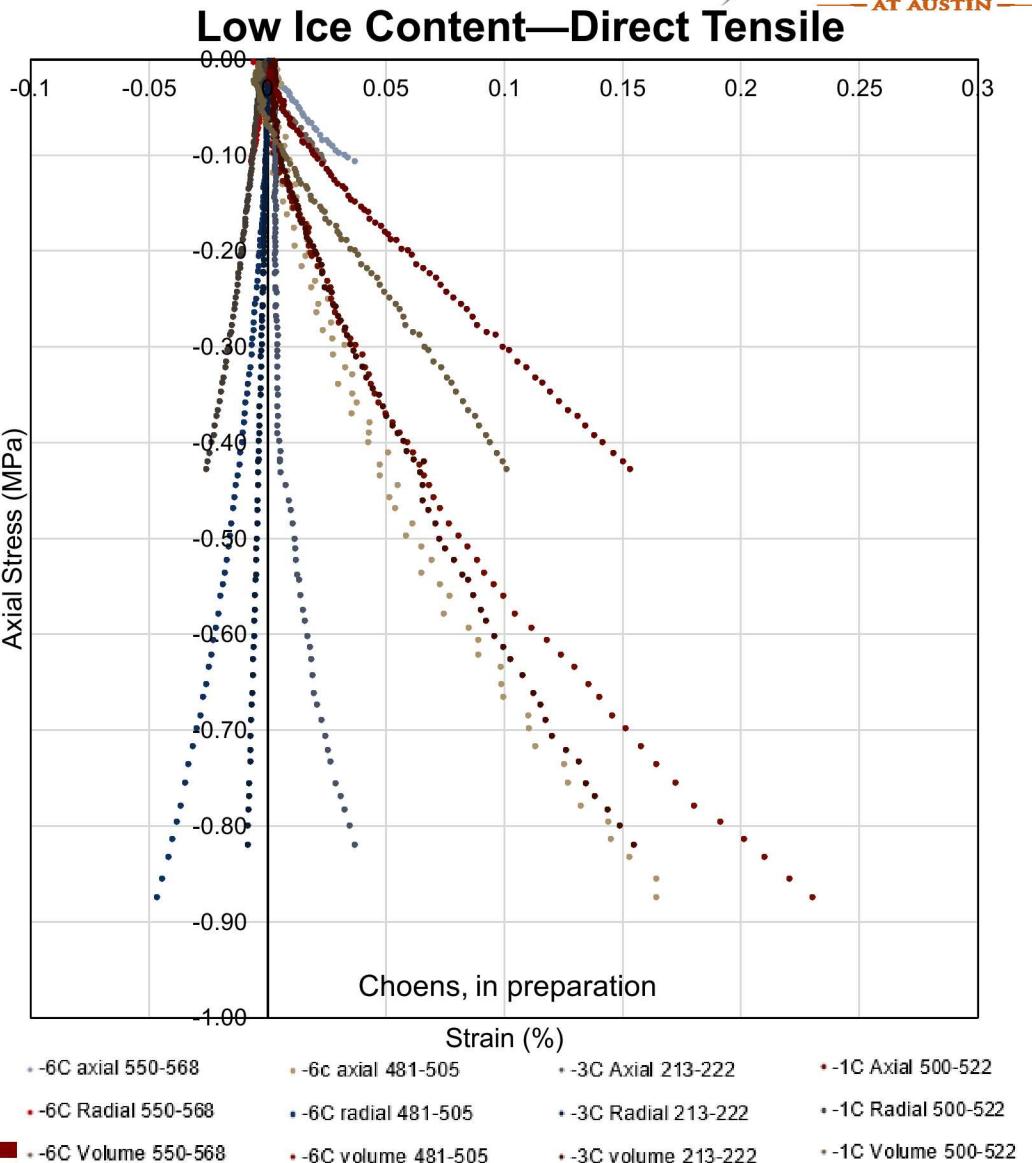


Albany is a finite deformation plasticity model

- 3x3 tensor of compressive, tensile, and shear components computed everywhere in the model (J2 class)
- Constitutive relationships require stress-strain curves up to failure as function of temperature and ice volume for local permafrost samples

SNL's Geomechanics Laboratory

- Environmental chamber to control temperature whilst performing unconfined compressive tests, direct tensile tests, and Brazilian tests



# Permafrost Geochemical Characterization

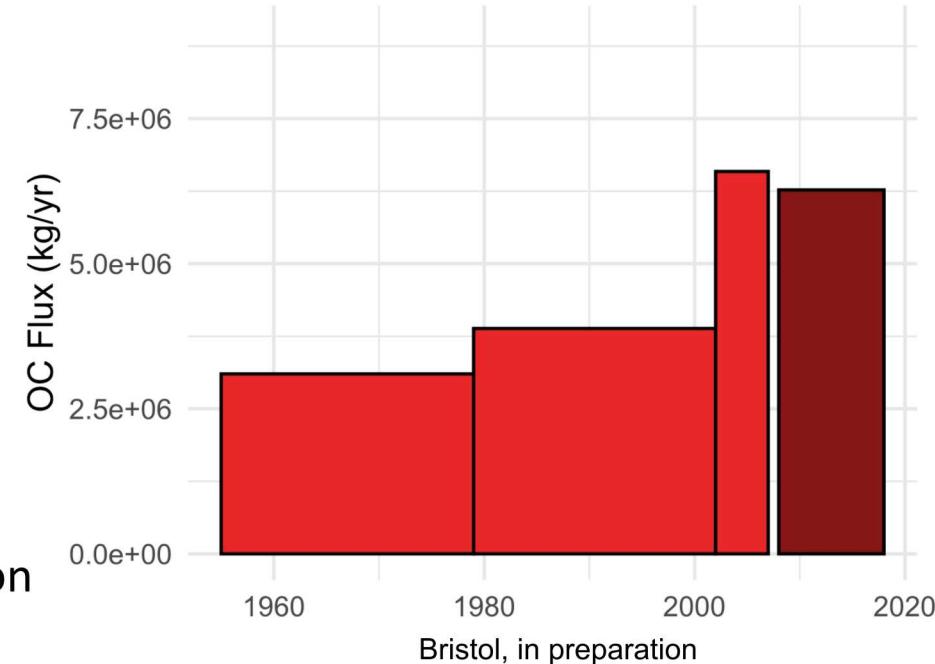


Total of 7 cores from Distinct Geomorphologies

- Up to 7.5m deep
- 3 span active layer to subsea

## Biogeochemical Analyses

- Establishing organic & inorganic compositions
  - C, N, P
  - Heavy metals, salts
- Estimating organic matter & nutrient fluxes into ocean
- Decomposition of organic carbon
  - DOC leaching & loss
  - $\text{CO}_2$  production in seawater

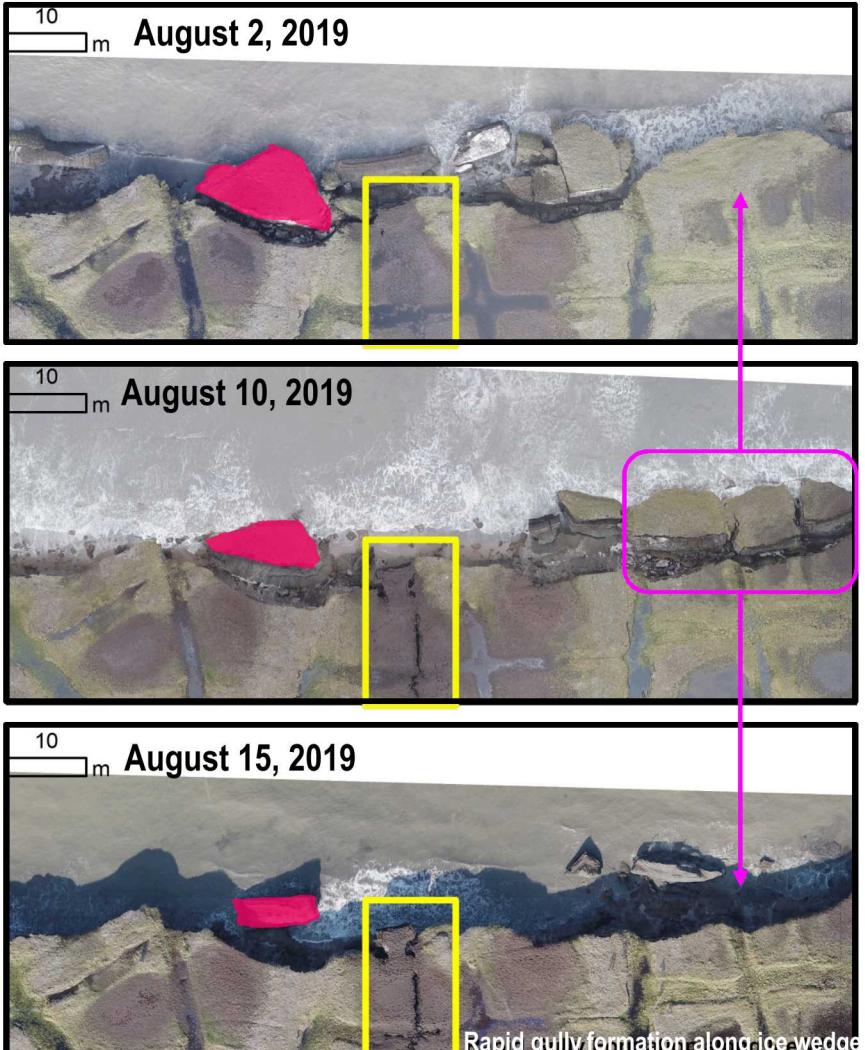


## Material Composition Analyses

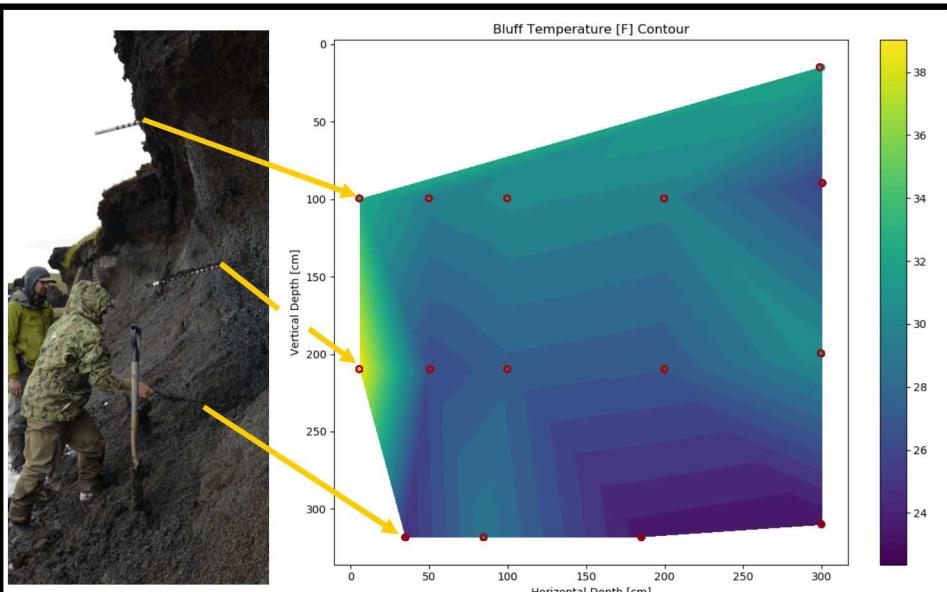
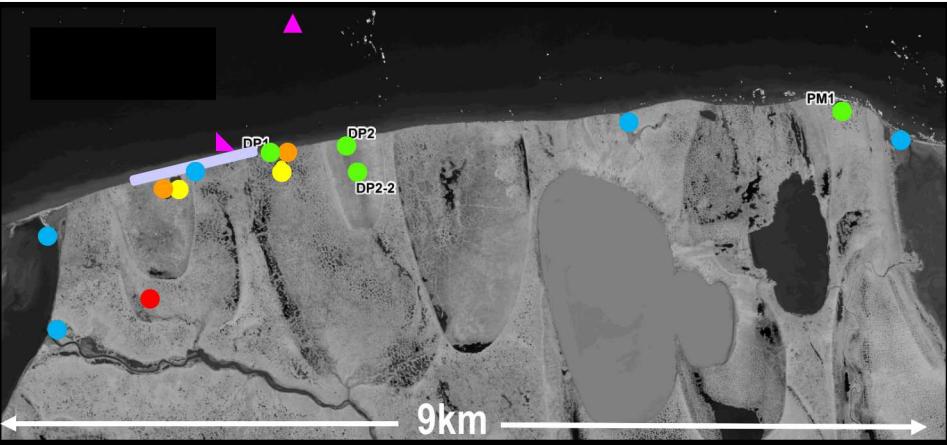
- Density, water content, & grain size

# FY19 Field Work

## Rapid Landscape Change Jones, in preparation



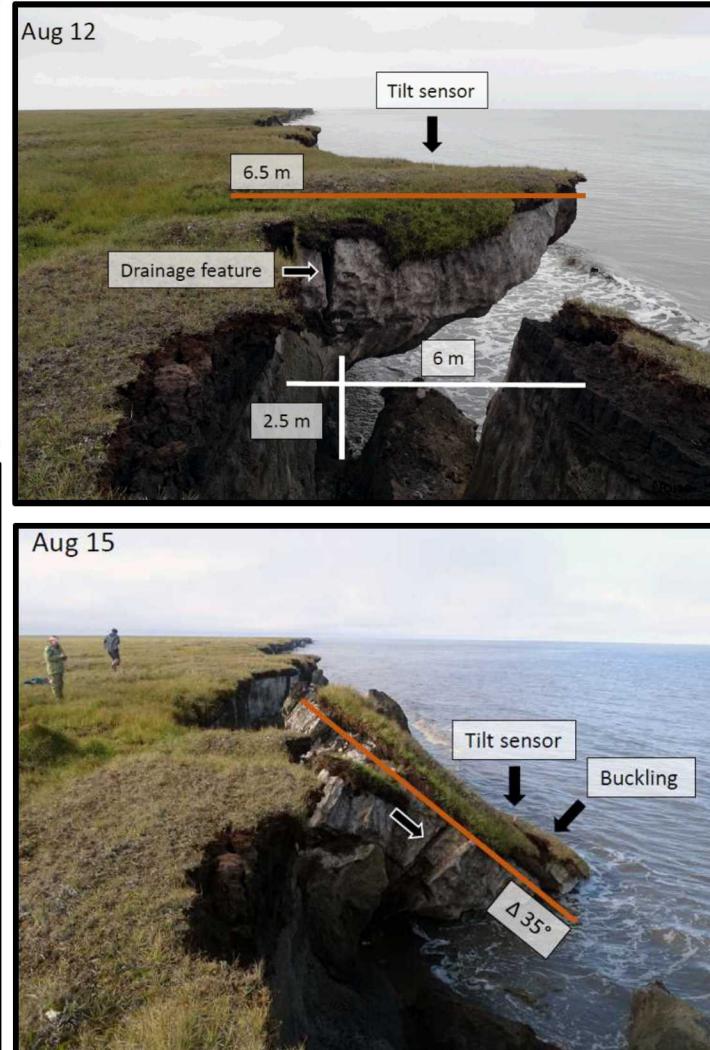
## Field Measurement Overview



## Thermal Measurements



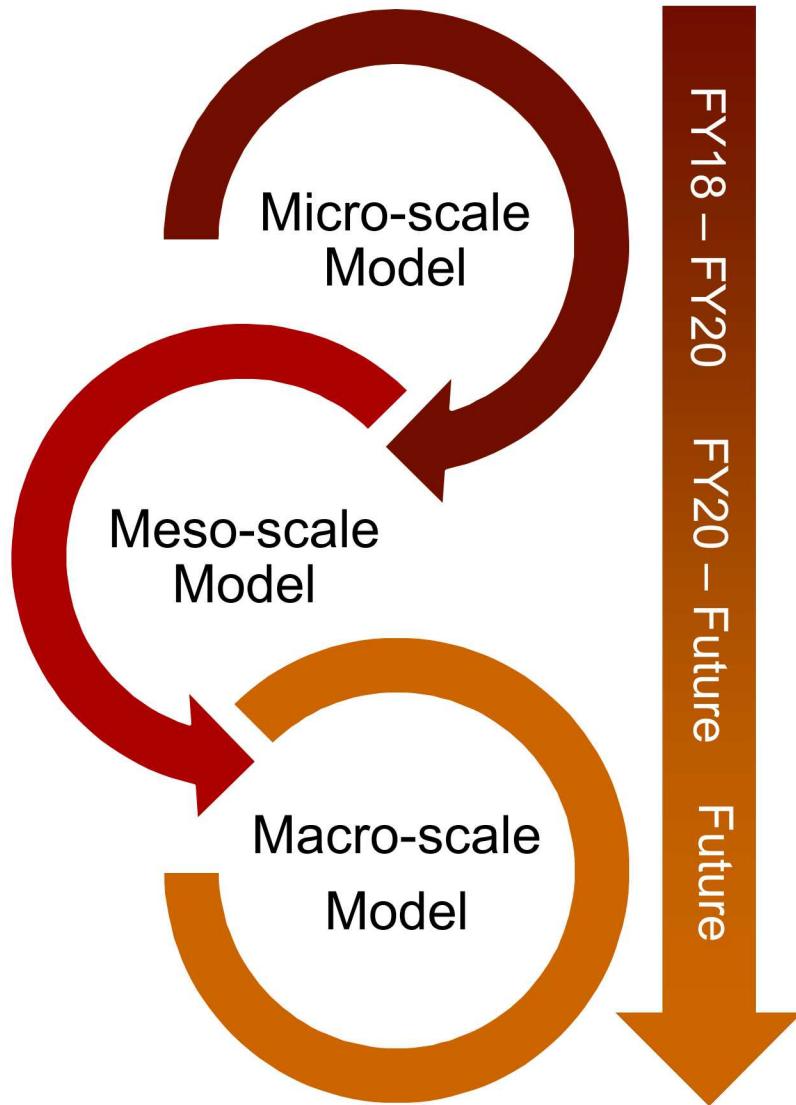
## Block Failure



FY18 – FY20

# SUMMARY

Project supported by the Laboratory Directed Research and Development program at Sandia National Laboratories.



# Goal: Flux Estimation & Impact

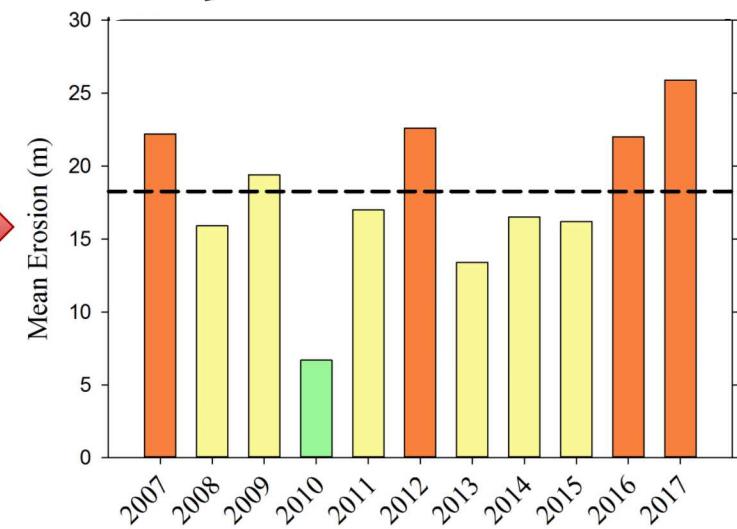
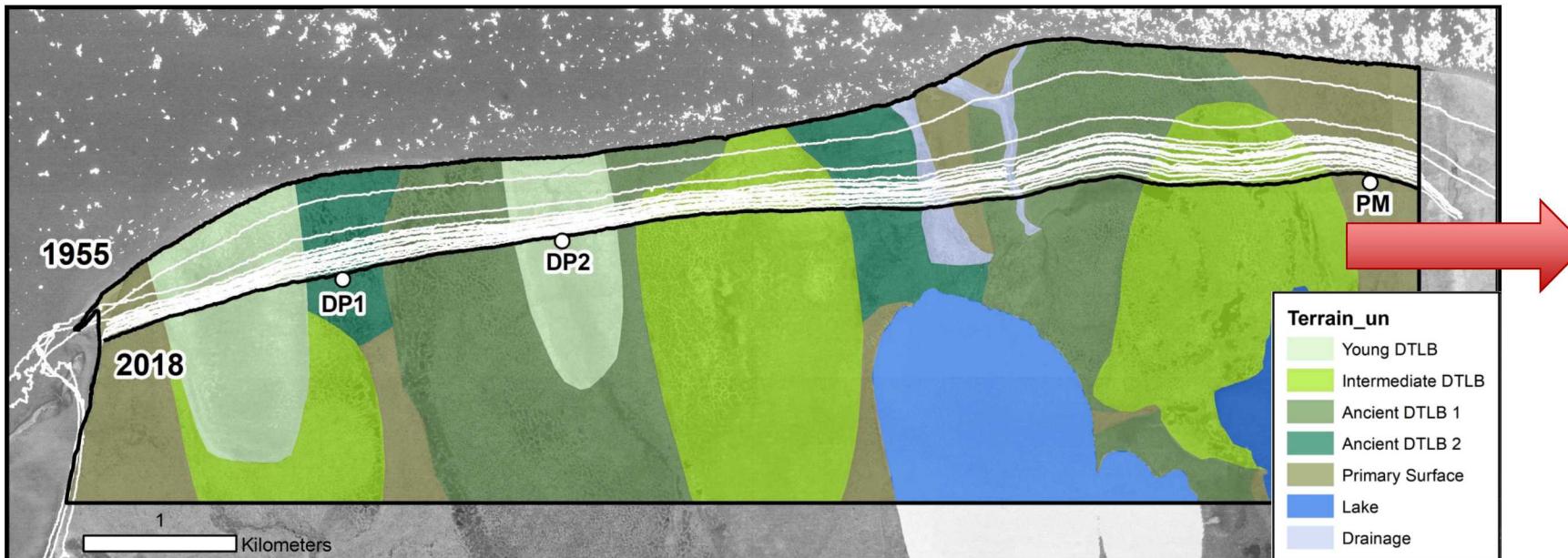
Estimate linear land losses based on high fidelity boundary conditions

Verify erosion amounts to determine near-shore inputs of:

- Sediments
- Nutrients
- Toxins

Determine recirculation of eroded materials

Partner to evaluate near-shore ecological stability



# Advancements

3-D 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, and
- an improved understanding of coastal food web impacts and carbon-climate feedbacks.

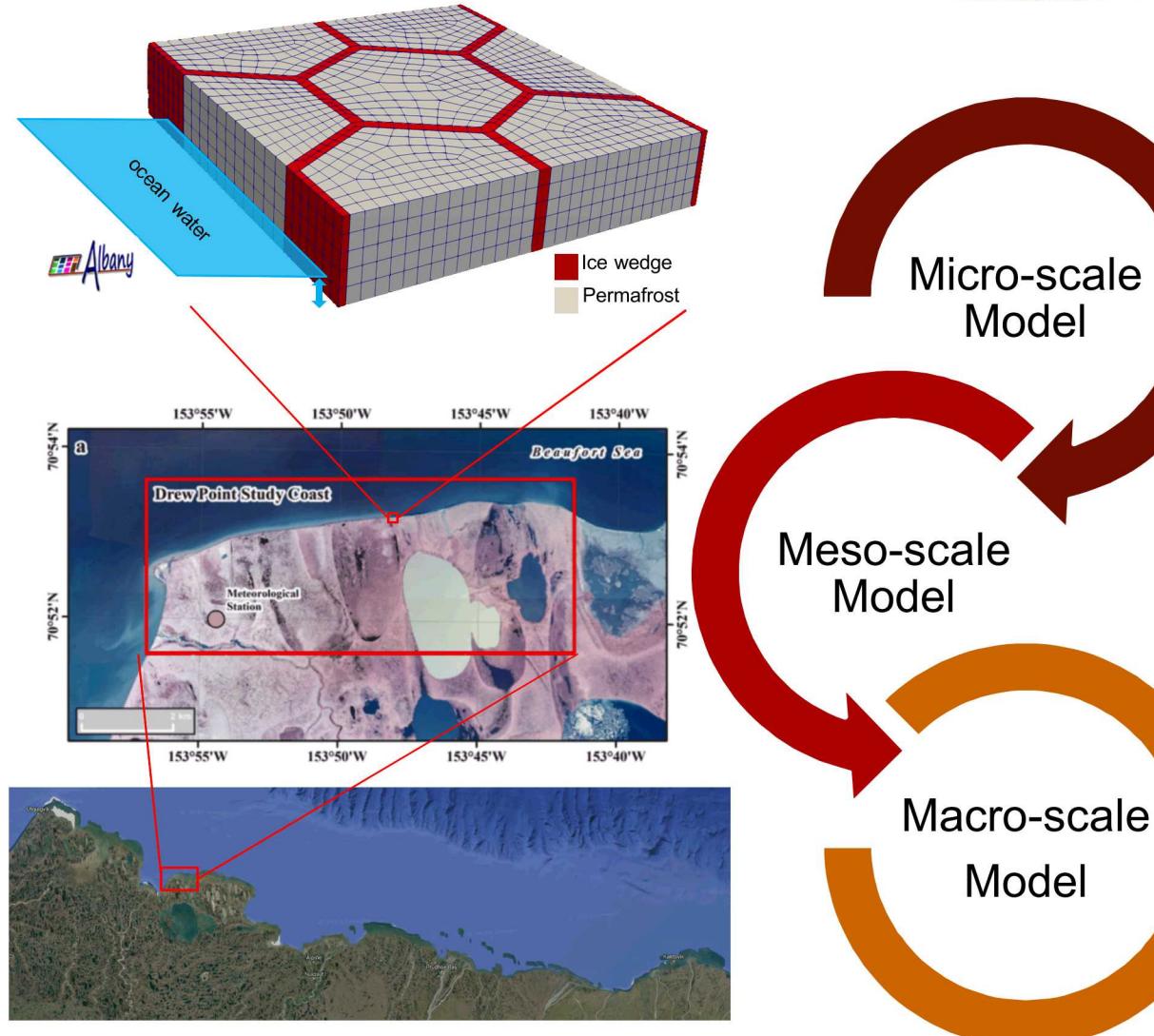


# Modeling Framework

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

- Member of the newly proposed DOE sponsored InteRFACE project focused on coastal processes in the Arctic

## INTERFACE





# POSTDOCTORAL APPOINTEE - MODELING AND SIMULATION OF CLIMATE PROCESSES IN THE ARCTIC

Posting # 670297 @ <https://www.sandia.gov/careers/> Open through January 4<sup>th</sup> 2020.

Come by the Sandia National Laboratories Booth, #231, for more information

## LEARN MORE WITH EMILY & MATT @ POSTER SESSION

**EMILY BRISTOL C13D-1343** - Geochemical characterization of eroding coastal permafrost and organic matter fluxes to the Beaufort Sea near Drew Point, Alaska

**MATT THOMAS C13D-1339** - Bluff geometry and material variability influence stress states relevant to coastal permafrost bluff failure

DIANA BULL. [DLBULL@SANDIA.GOV](mailto:DLBULL@SANDIA.GOV)



# QUESTIONS



# QUESTIONS



# References

## Title slide photos (in order)

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B. Jones, U.S. Geological Survey

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