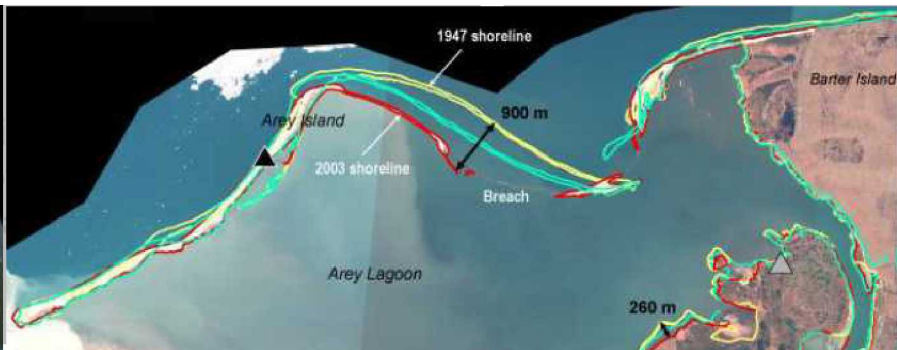
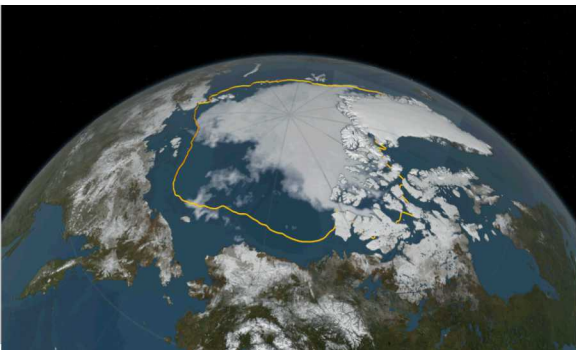


Development of a Tightly Coupled Multi-Physics Numerical Model for an Event-Based Understanding of Arctic Coastal Erosion

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



# 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

PI: Diana Bull, PM: Lori Parrott

Emily Bristol, Charles Choens, Craig Connolly, Chris Flanary, Jennifer Frederick, Ben Jones, Craig Jones, Jeremy Kasper, Jim McClelland, Alejandro Mota, Siddharth Namachivayam, Matt Thomas

# MOTIVATION

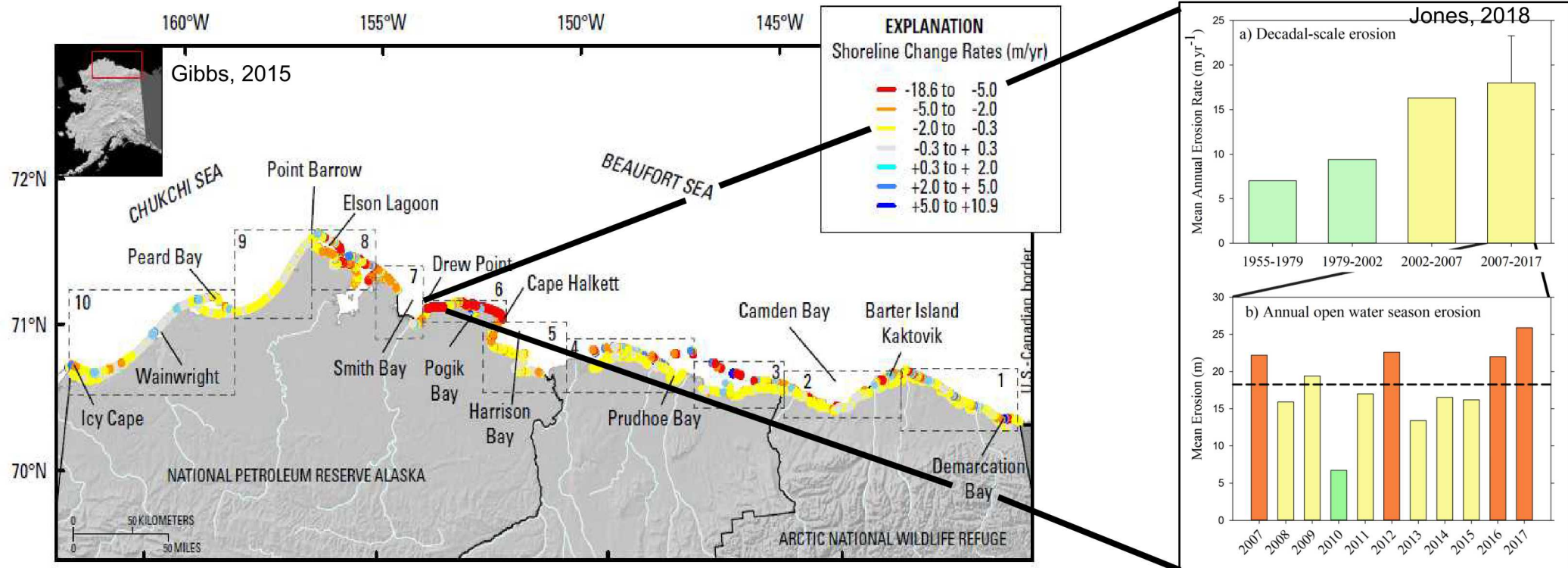
# Problem Statement

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!!



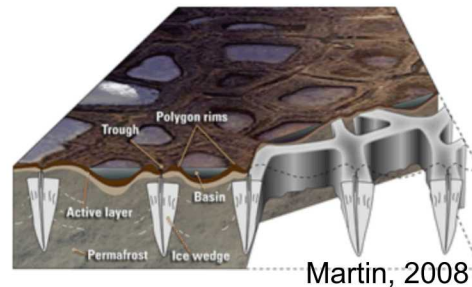
# State of the Technology

Unique erosion process in Arctic:

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

Erosion dependent characteristics

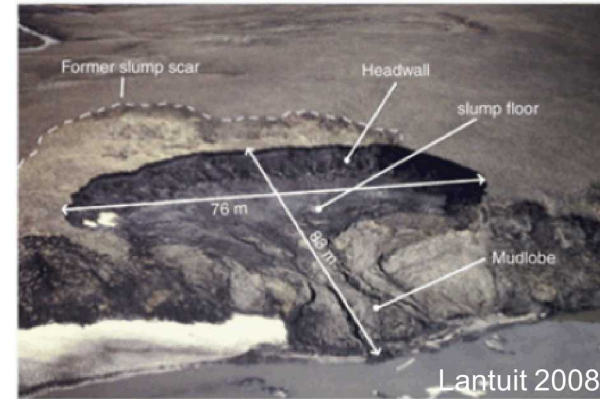
- Geomorphology
- Geophysics
- Boundary Conditions



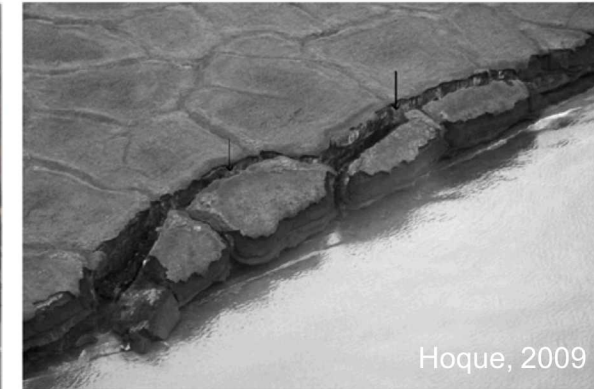
State of the art permafrost erosion modeling

- 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



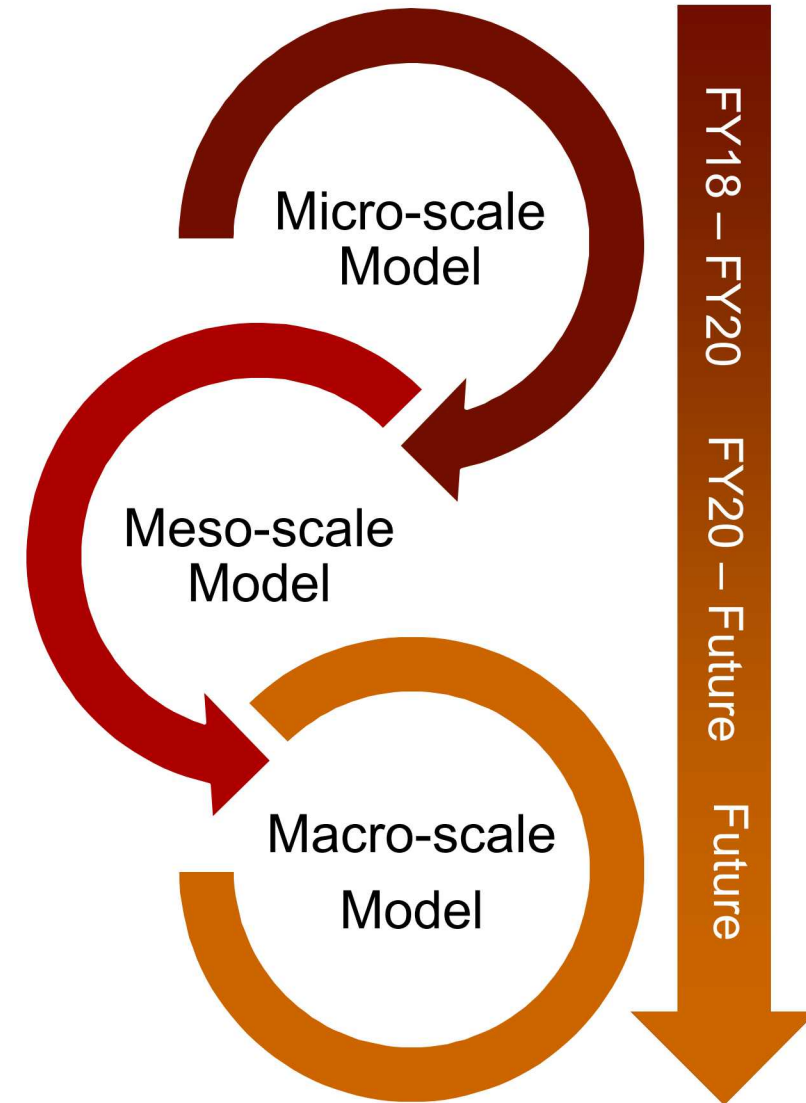
active layer detachment



FY18 – FY20

# ARCTIC COASTAL EROSION (ACE) MODELING APPROACH

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



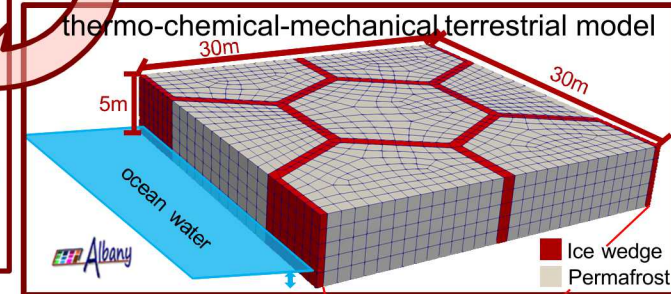
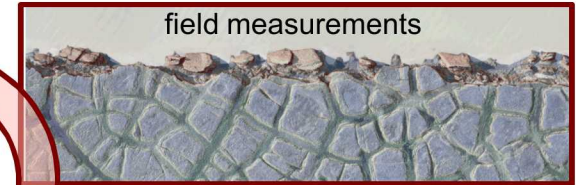
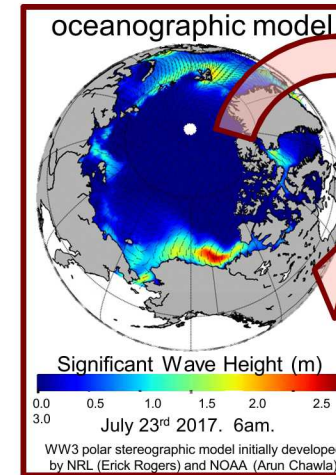


# Proposed Solution

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

**2018-2020** **Micro-scale Model**  
10's of meters & storm duration

- 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



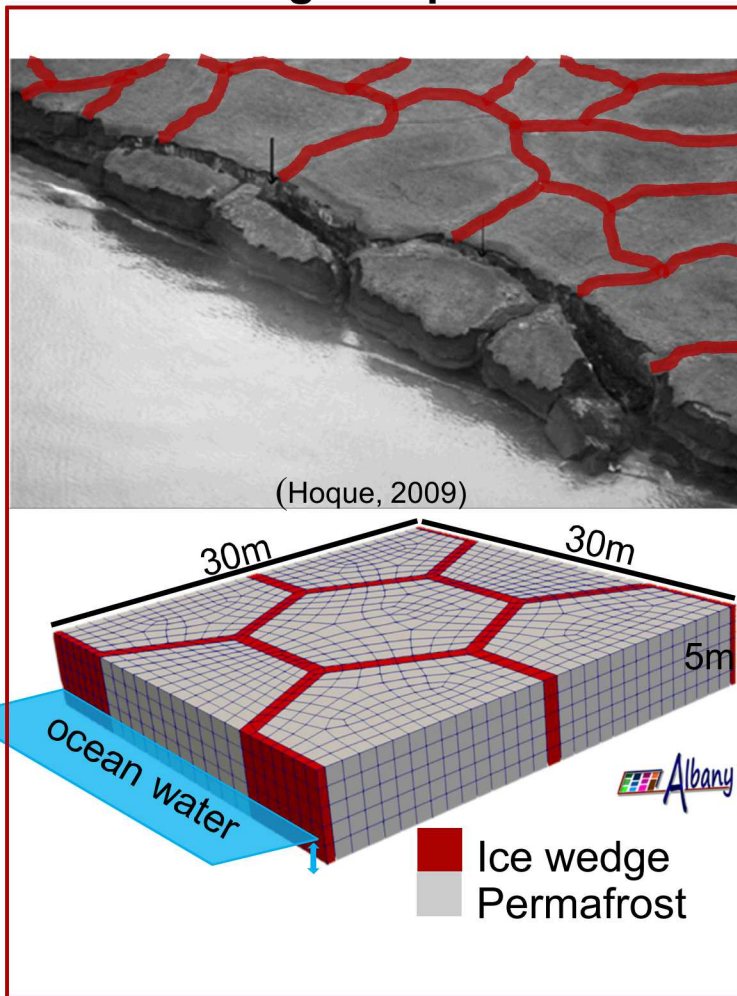
**2020-future** **Meso-scale Model**  
10's of km's & seasonal duration

- 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



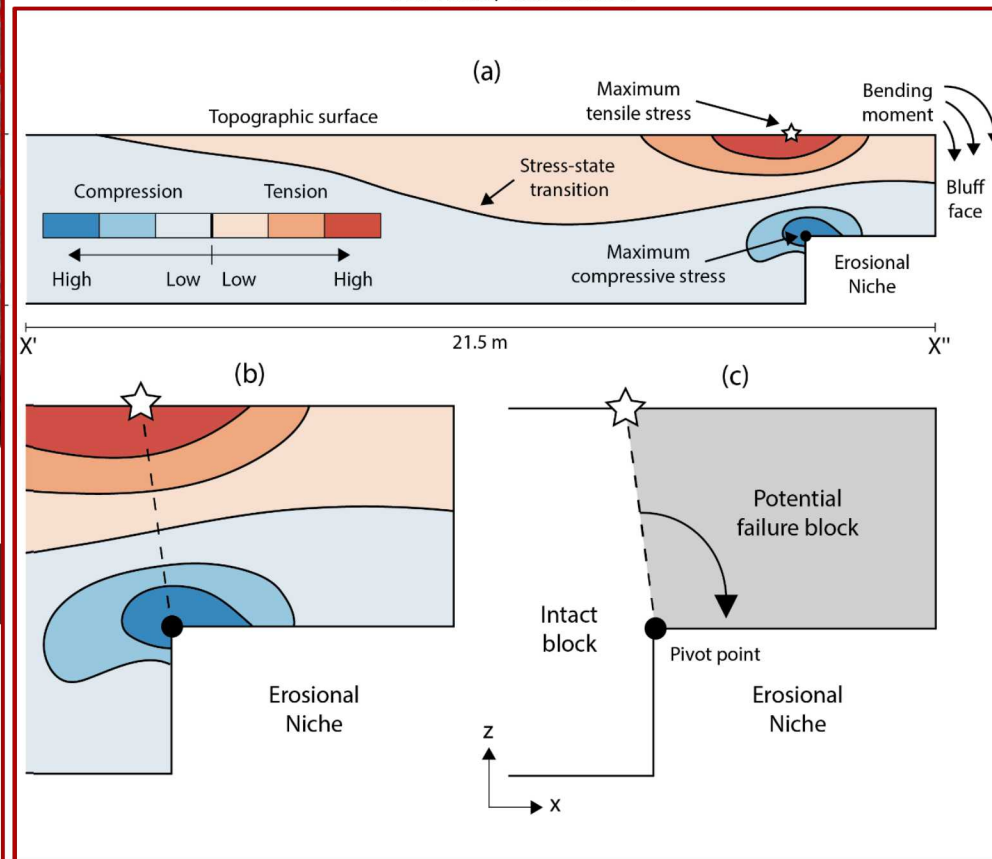
# Focus: Block Failure

## Modeling Interpretation



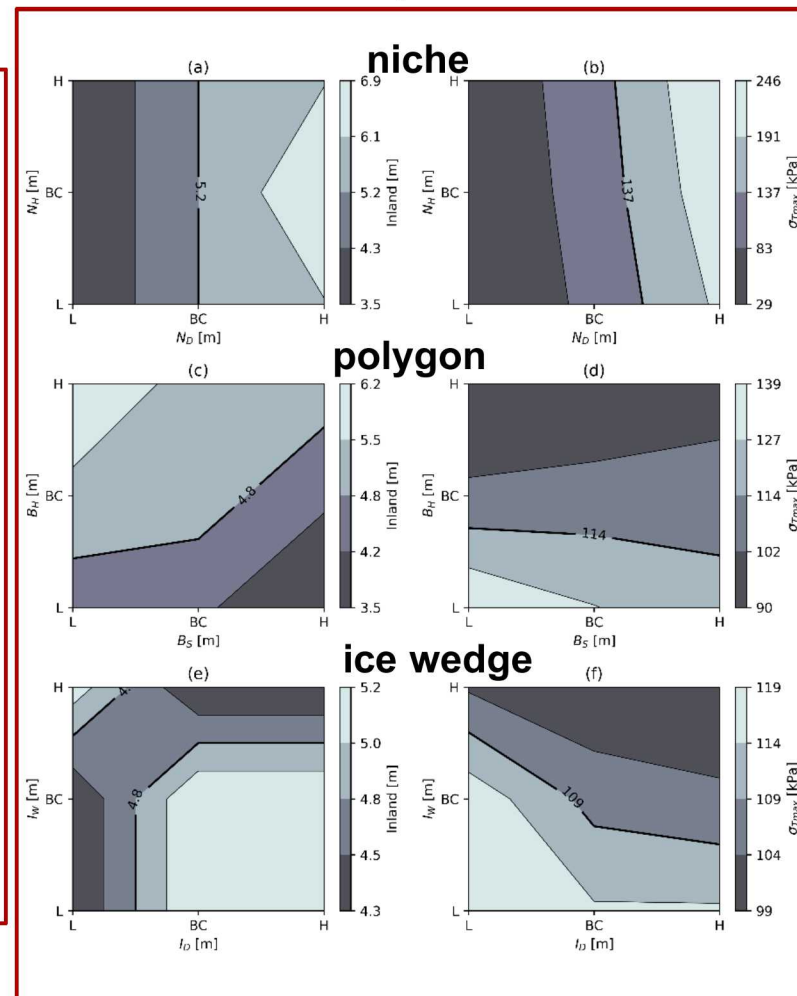
## Conceptual Model of Stress Field

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

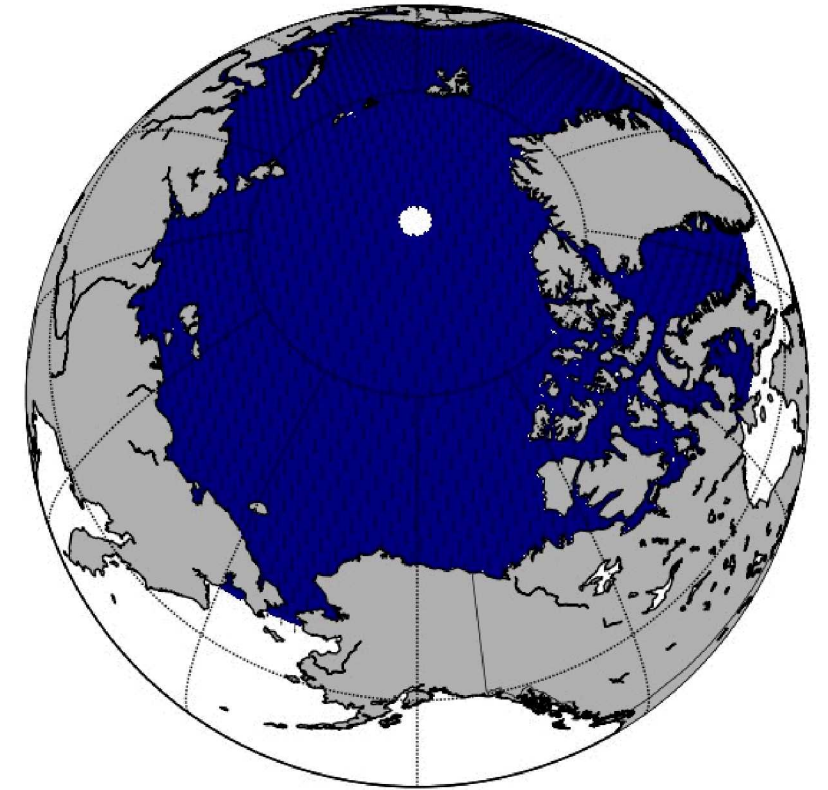
- capture induced currents in nearshore
- capture set-up (storm surge and runup)

## 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

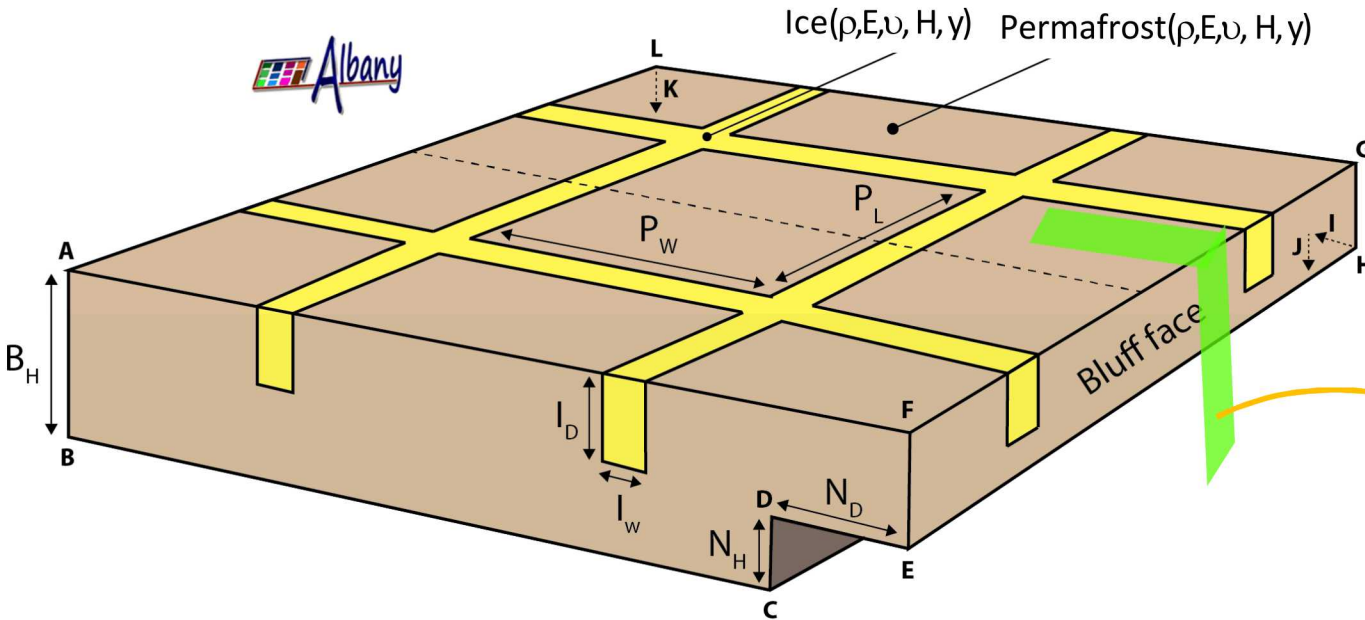
Flanary, in preparation



0.0 0.5 1.0 1.5 2.0 2.5 3.0  
Sig. Wave Height (m)  
WW3 polar stereographic model initially developed by NRL (Erick Rogers) and NOAA (Arun Chawla)

# Terrestrial Modeling

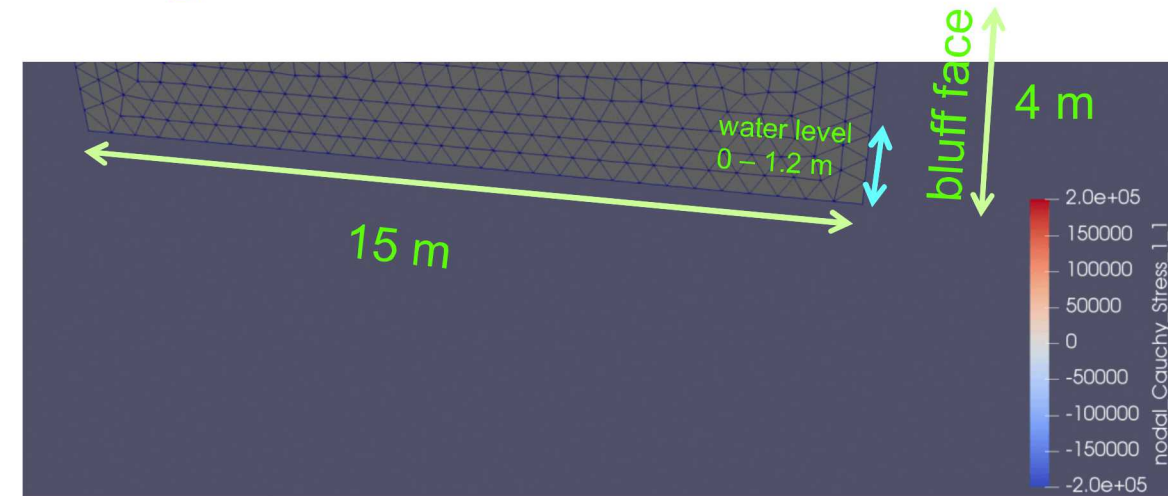
Frederick & Mota, in preparation



2D bluff cross section of stress

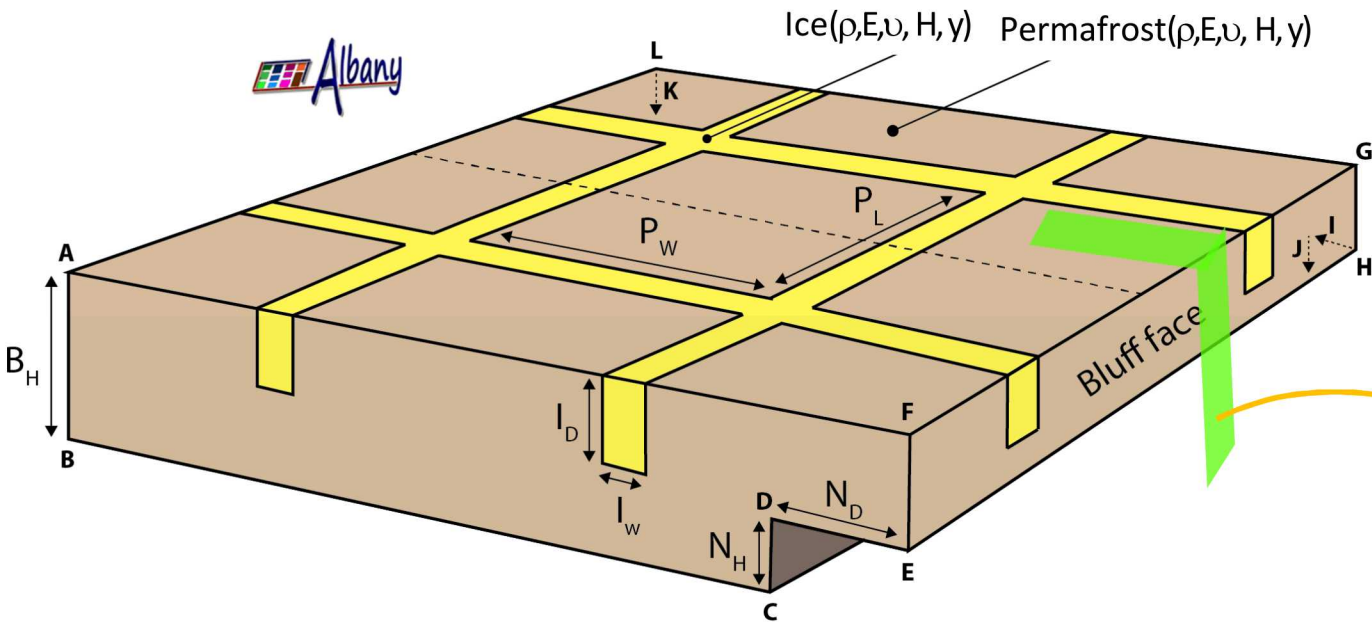
## Key Advances

- 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

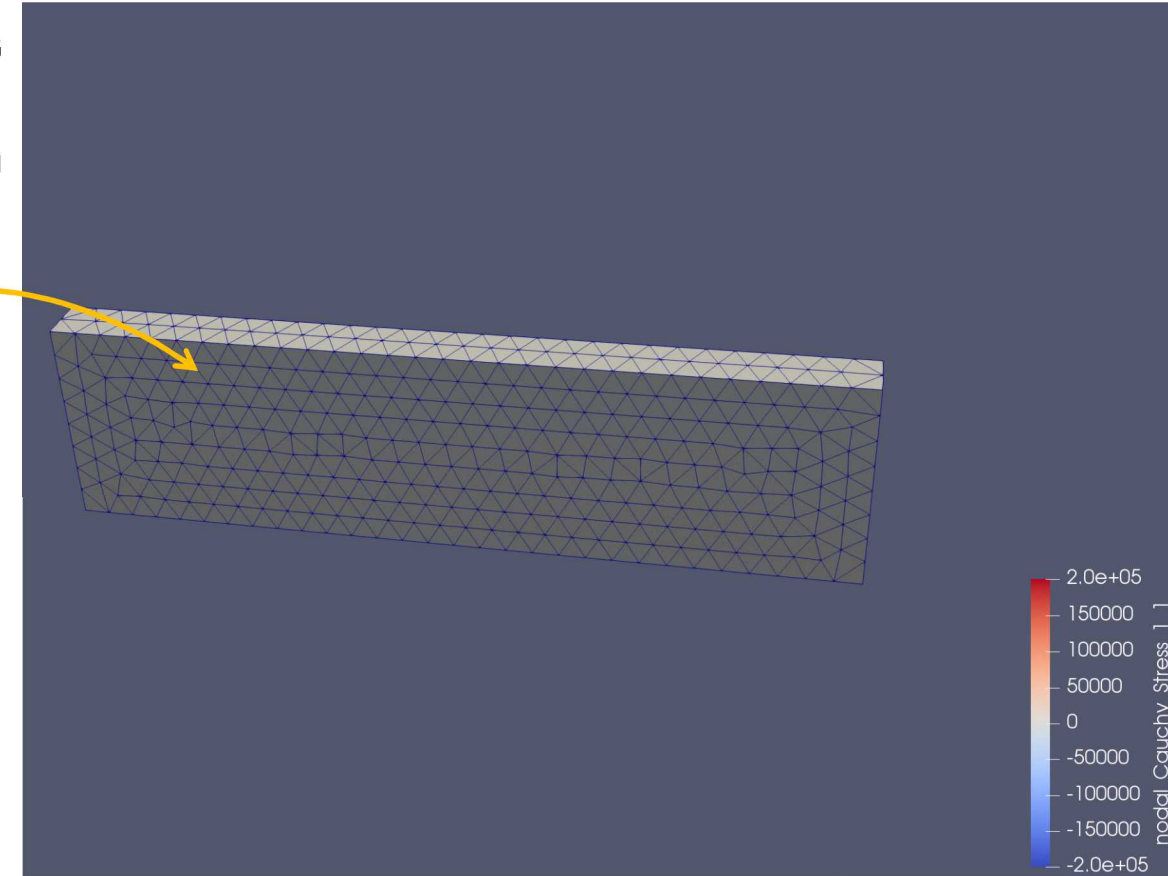




# Terrestrial Modeling



Frederick & Mota, in preparation



## Key Advances

- 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



# Coupled Thermal-Mechanical Response

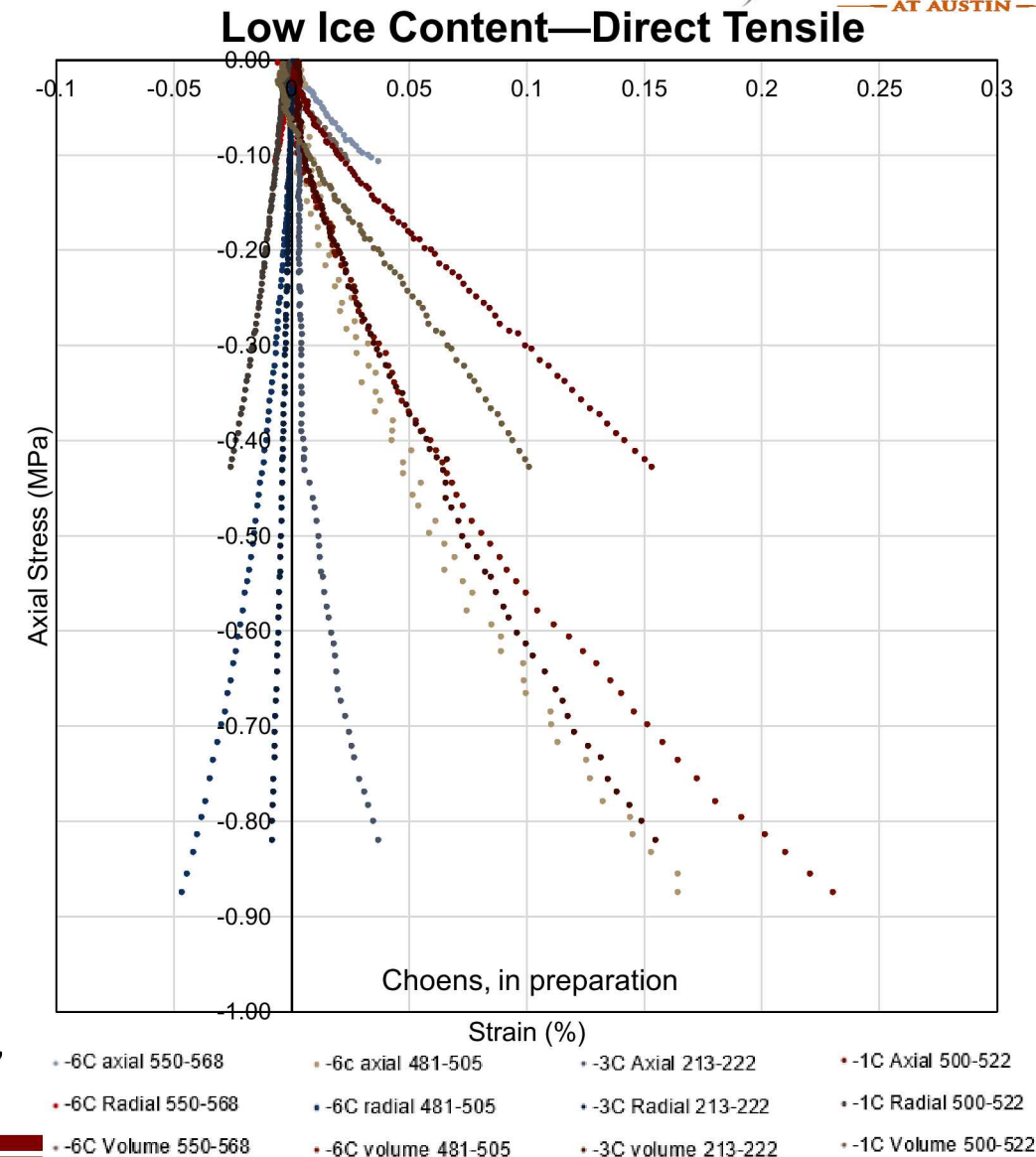


Albany is a finite deformation plasticity model

- 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



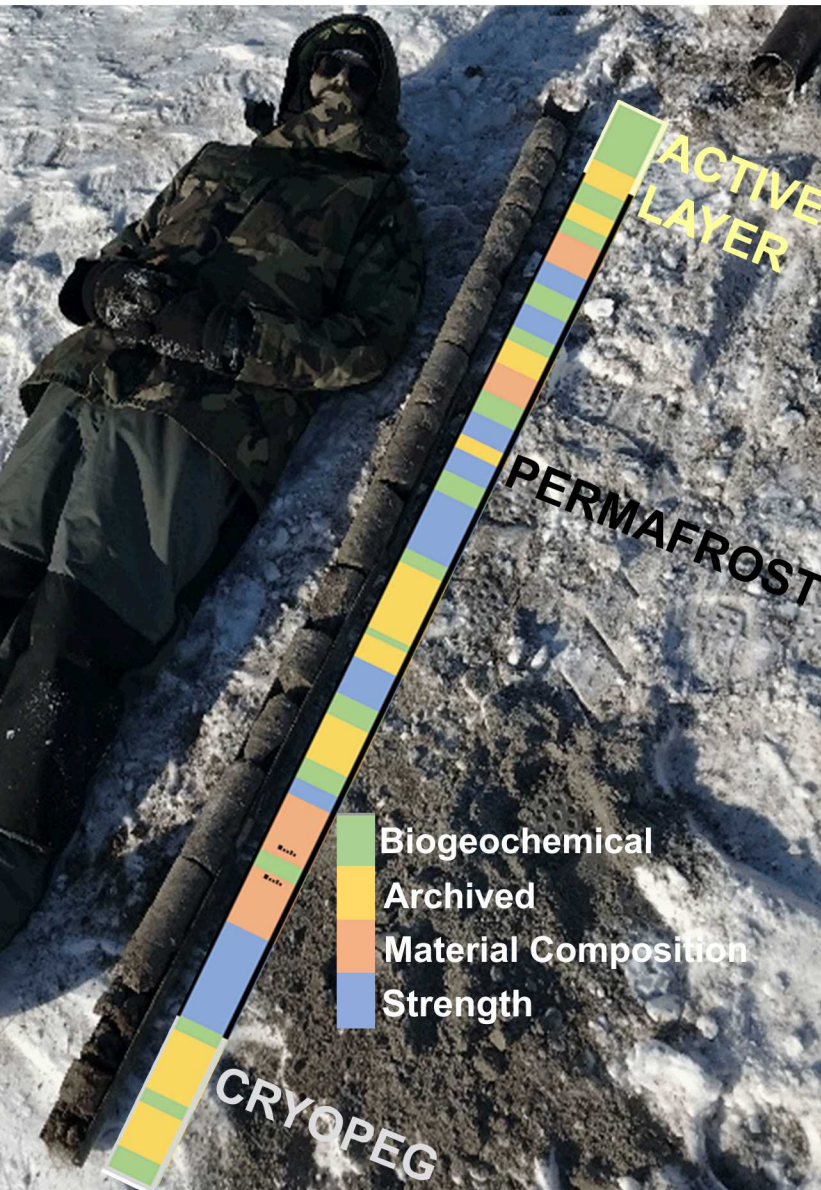
Sandia  
National  
Laboratories



integral  
consulting inc.



THE UNIVERSITY OF  
TEXAS  
AT AUSTIN

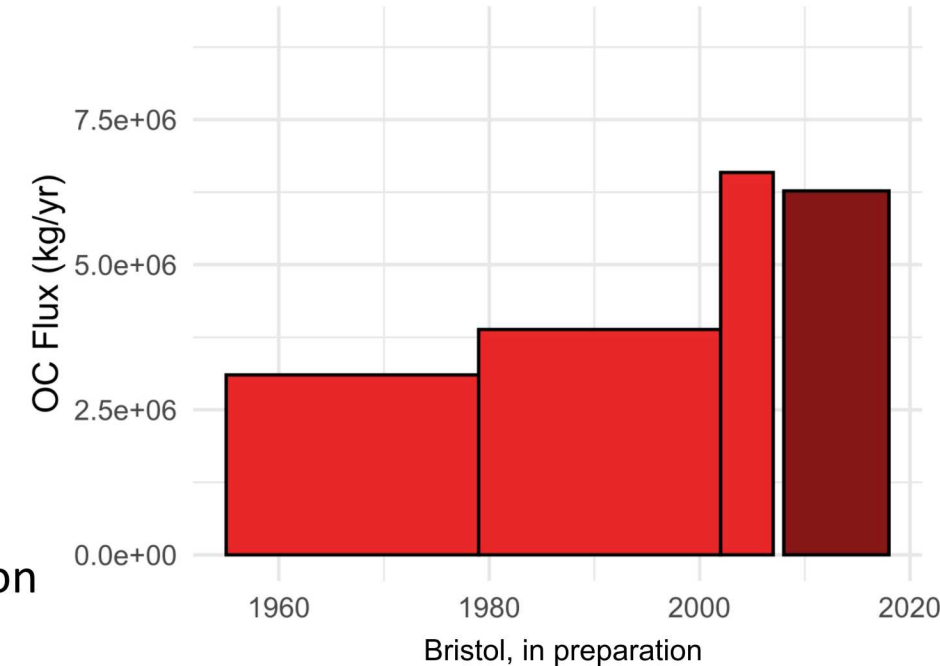


Total of 7 cores from Distinct Geomorphologies

- 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
  - CO<sub>2</sub> production in seawater



## Material Composition Analyses

- Density, water content, & grain size

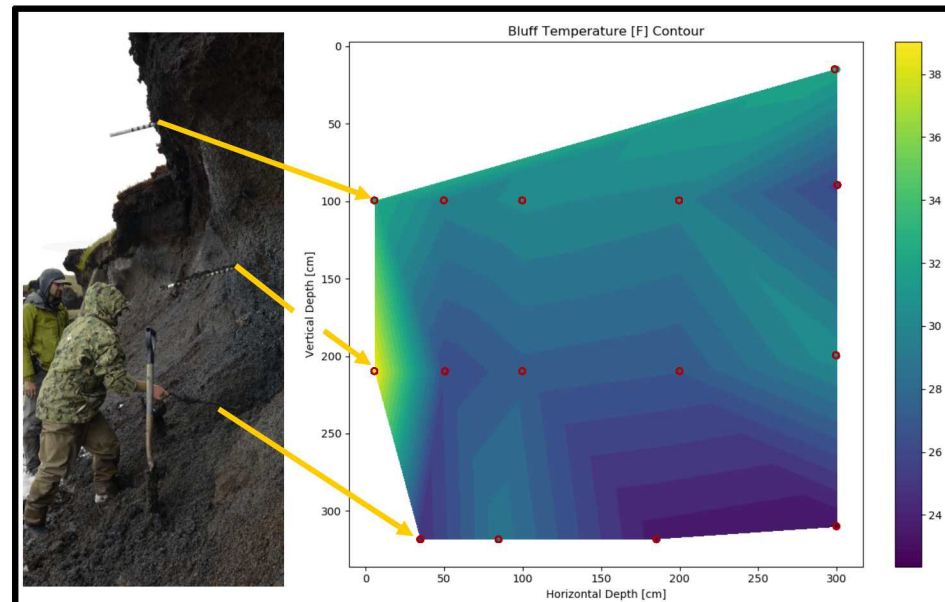
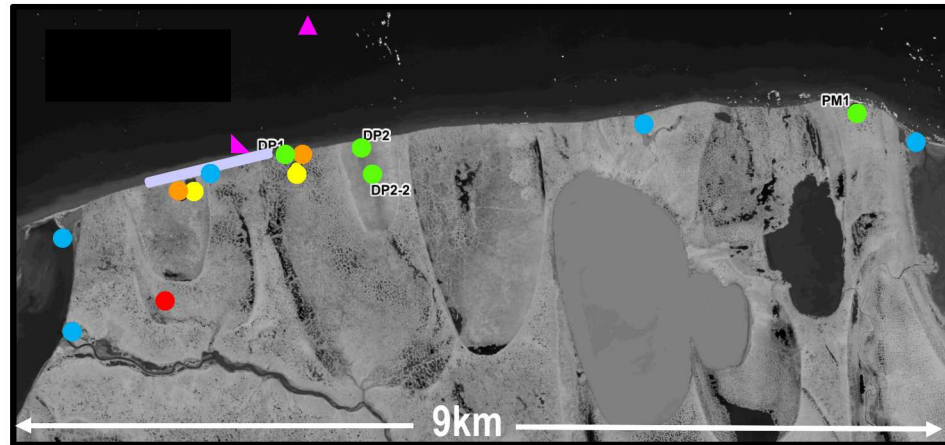


# FY19 Field Work

## Rapid Landscape Change Jones, in preparation

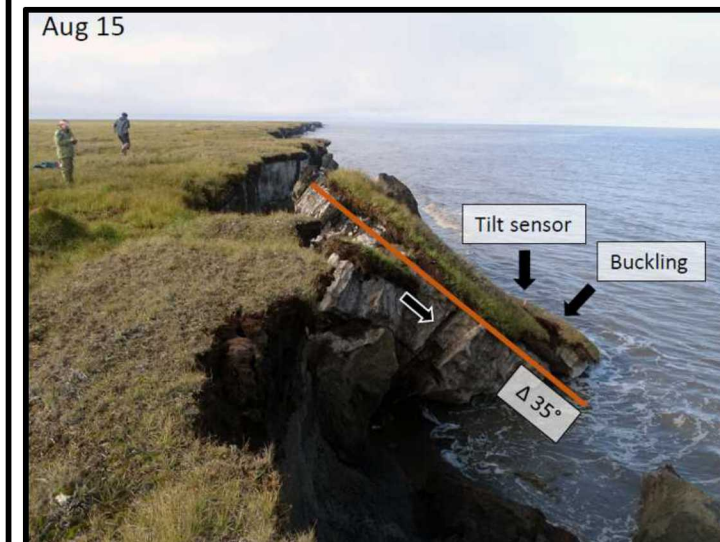
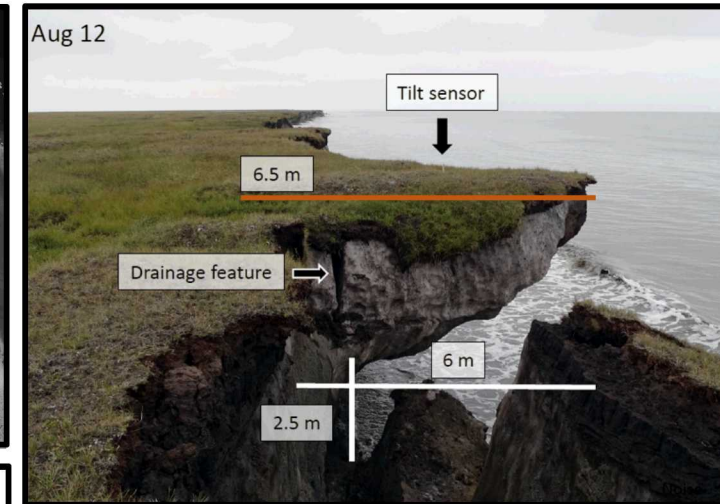


## Field Measurement Overview



## Thermal Measurements

## Block Failure

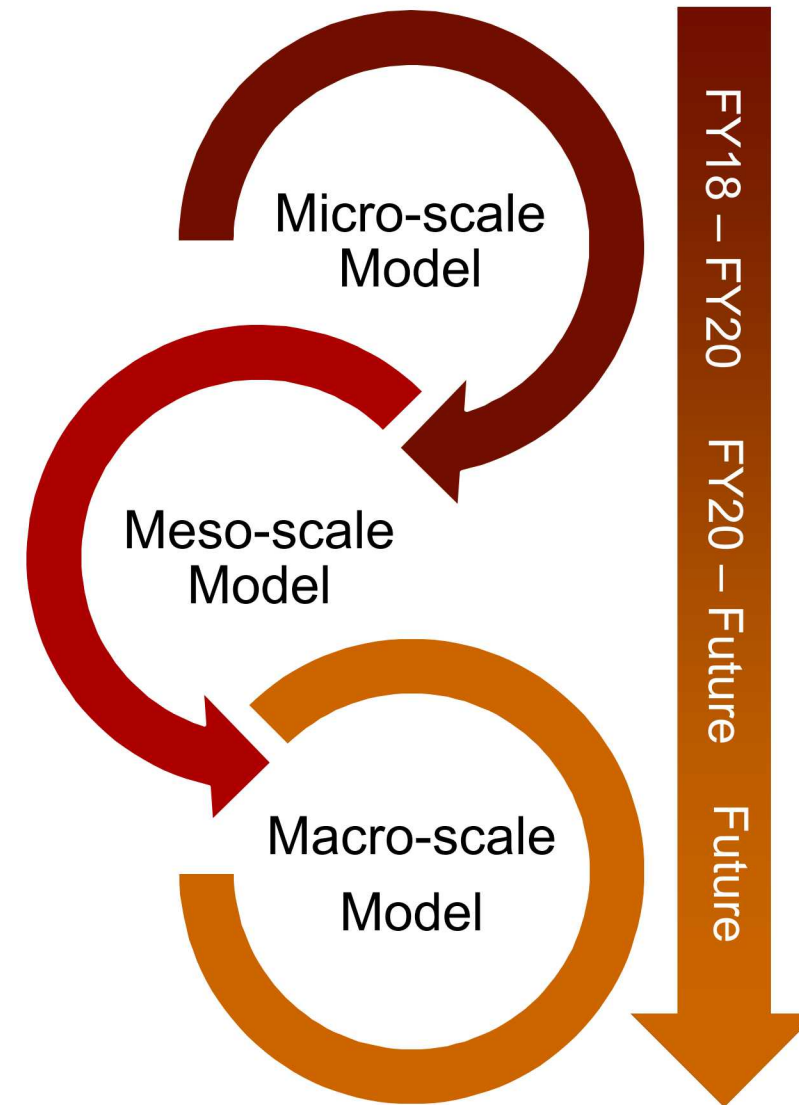




FY18 – FY20

## SUMMARY

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



# Goal: Flux Estimation & Impact

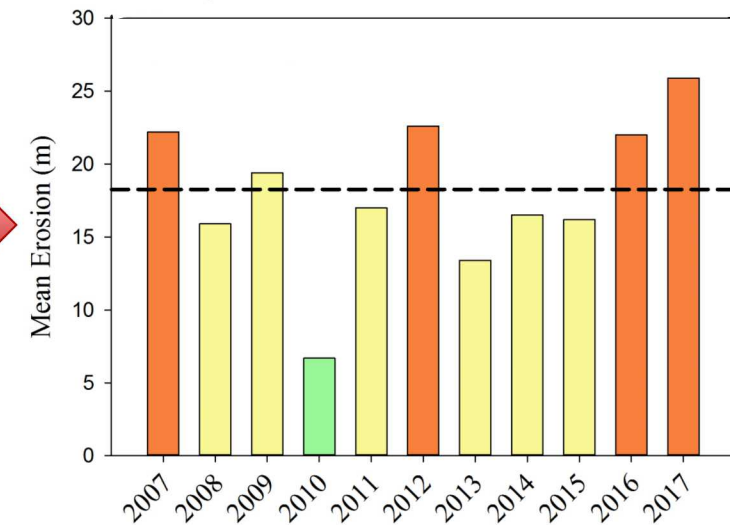
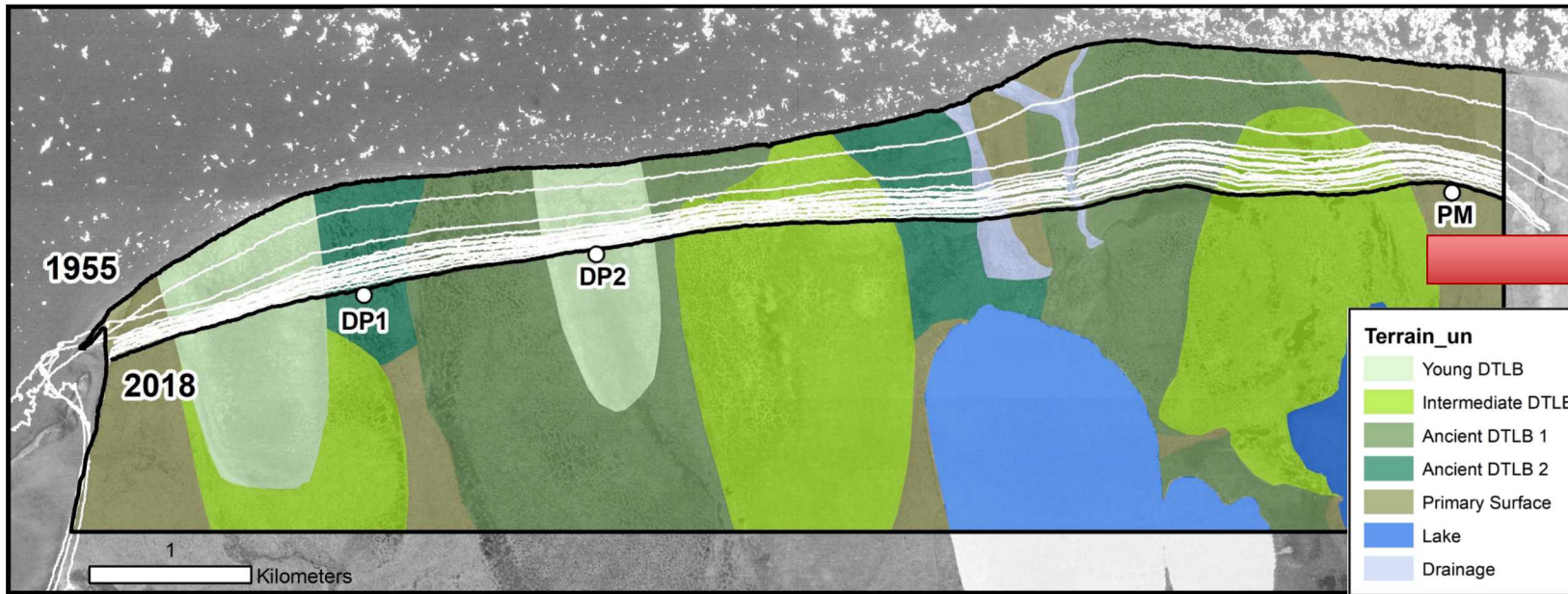
Estimate linear land losses based on high fidelity boundary conditions

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.



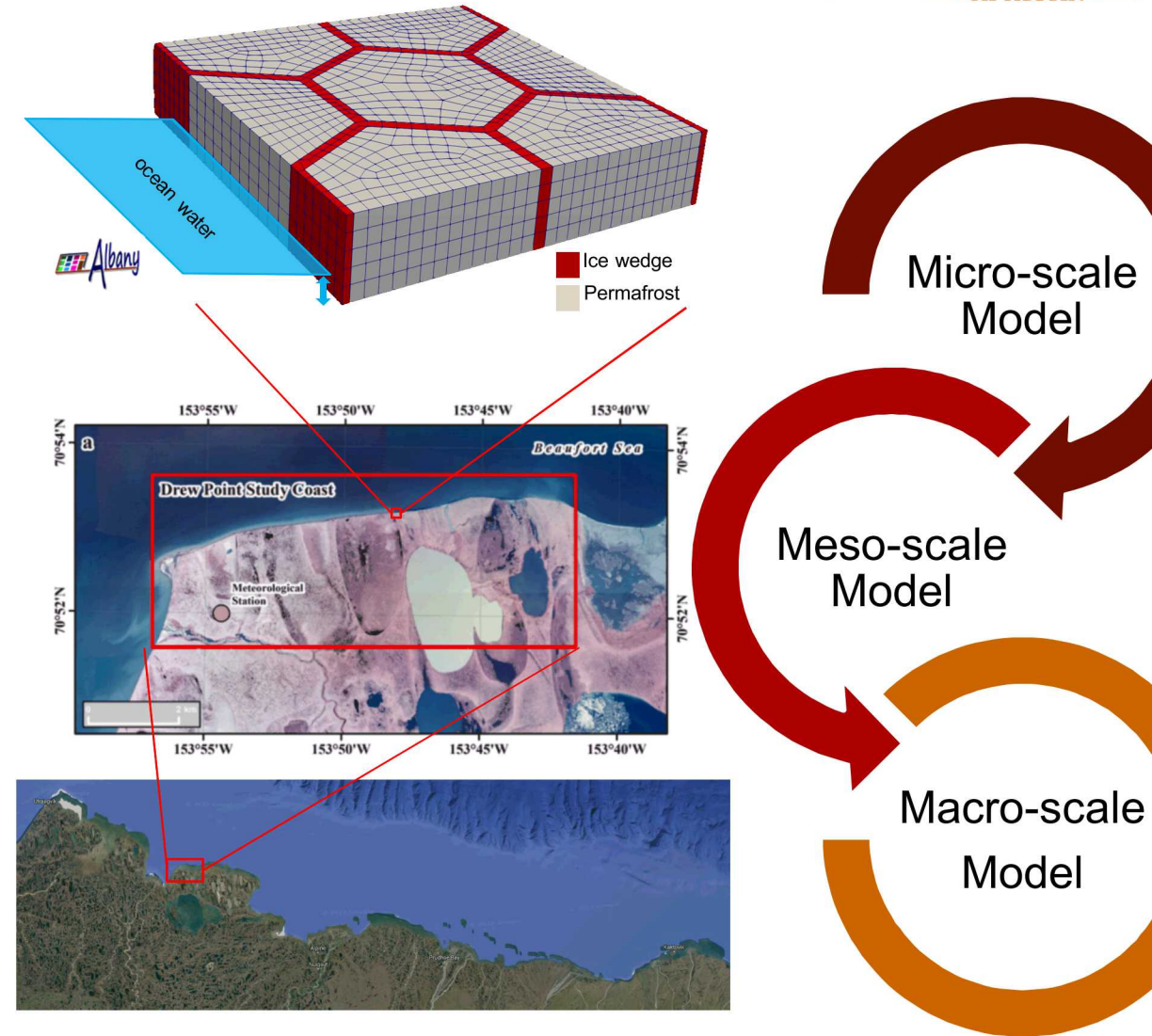


# Modeling Framework

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

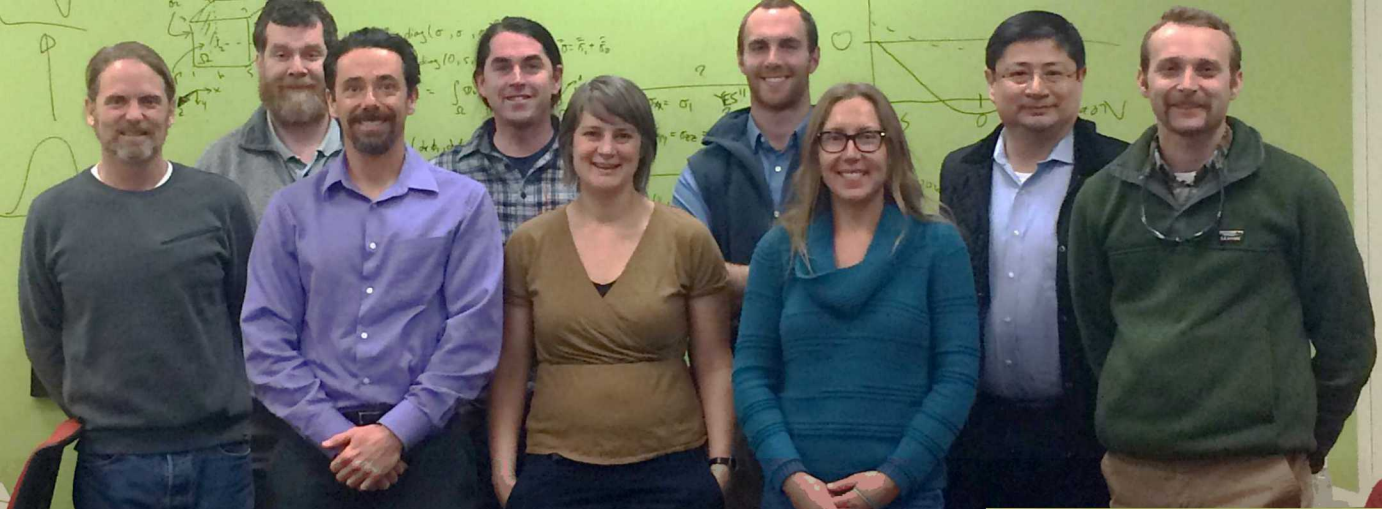
## LEARN MORE WITH EMILY & MATT @ POSTER SESSION

**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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[6] Lantuit, H. and W.H. Pollard. 2008. Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada. *Geomorphology*, 95, 84-102.

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[9] Thomas, M., A. Mota, B. M. Jones, R. C. Choens, J. M. Frederick, and D. L. Bull. Examining the influence of geometric and material variability on simulated stress states relevant to coastal permafrost bluff failure. *Frontiers in Earth Science – Cryospheric Sciences*. Submitted October 2019.