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Sandia National Laboratories

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Probabilistic Predictions of Offshore Gas Hydrate and Submarine Permafrost Distribution Along the Alaskan North Slope

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PURPOSE, GOALS AND APPROACH

PURPOSE

Geospatial Machine Learning Prediction + Sediment Thermodynamic Physical Modeling = **Creation of *Probabilistic* Maps** of Free Gas, Gas Hydrate, and Submarine Permafrost Distribution, and resulting Geo-acoustic/Geo-mechanical Properties

APPLICATIONS

Allows more accurate **natural resource quantification** for energy security.

Can inform climate models on **greenhouse gas releases** and carbon cycling.

Maps can support **Naval operations** that rely on SONAR performance and **sound propagation models.**

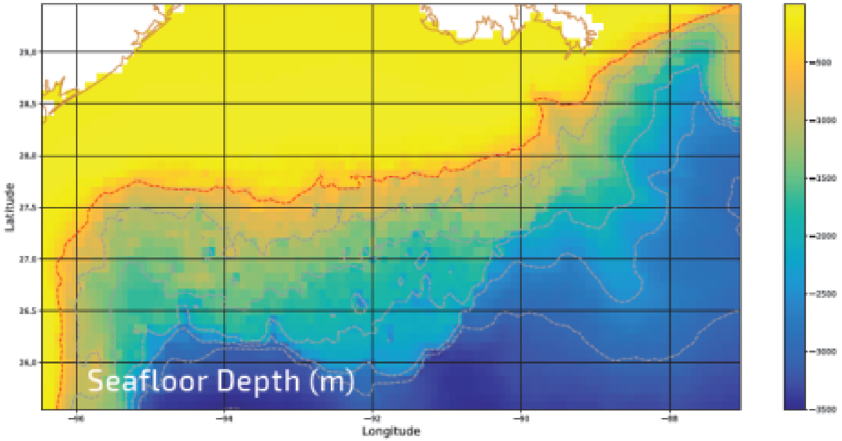
APPROACH

Ensemble modeling can produce probabilistic maps give the **most likely value** of any characteristic of interest, but also its **variation and range**.

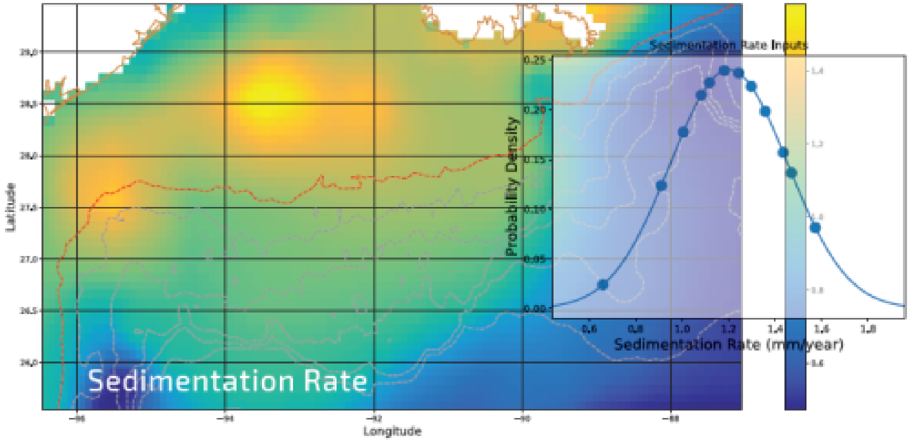
Analogous to a weather forecast: although it is uncertain, it is more useful than a single deterministic forecast.

Ensemble Modeling Approach, An Example

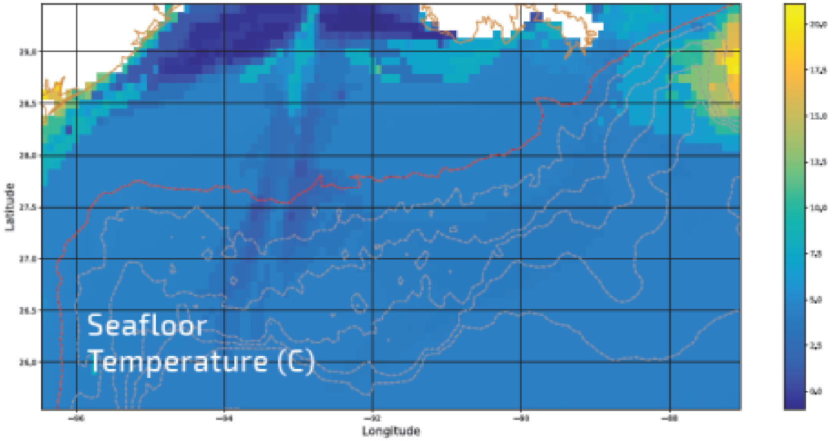
Naval Research Lab's geospatial machine learning maps of input parameters at the Gulf of Mexico:



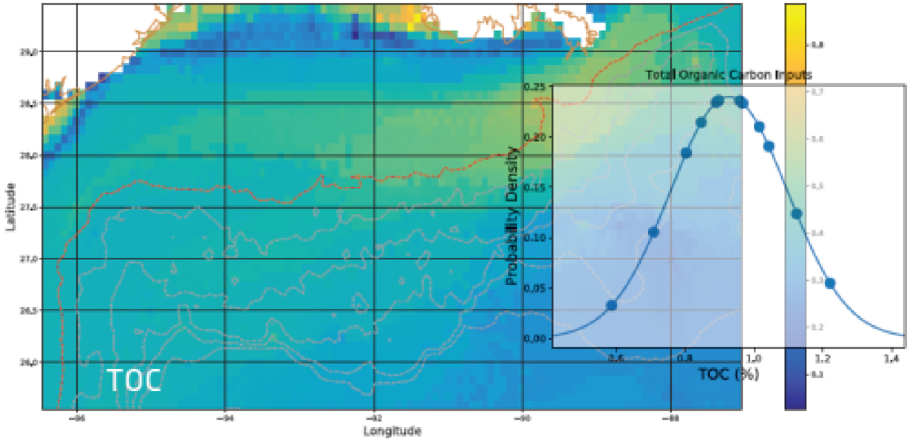
National Geophysical Data Center. (2006). 2-minute gridded global relief data (ETOPO2) v2.



Straume, et al. (2019). GlobSed: Updated total sediment thickness in the world's oceans. G3, 20(4), 1756-1772.
Müller, et al. (2008). Age, spreading rates, and spreading asymmetry of the world's ocean crust. G3, 9(4).



Locarnini, et al. (2013). World ocean atlas 2013. Volume 1, Temperature.



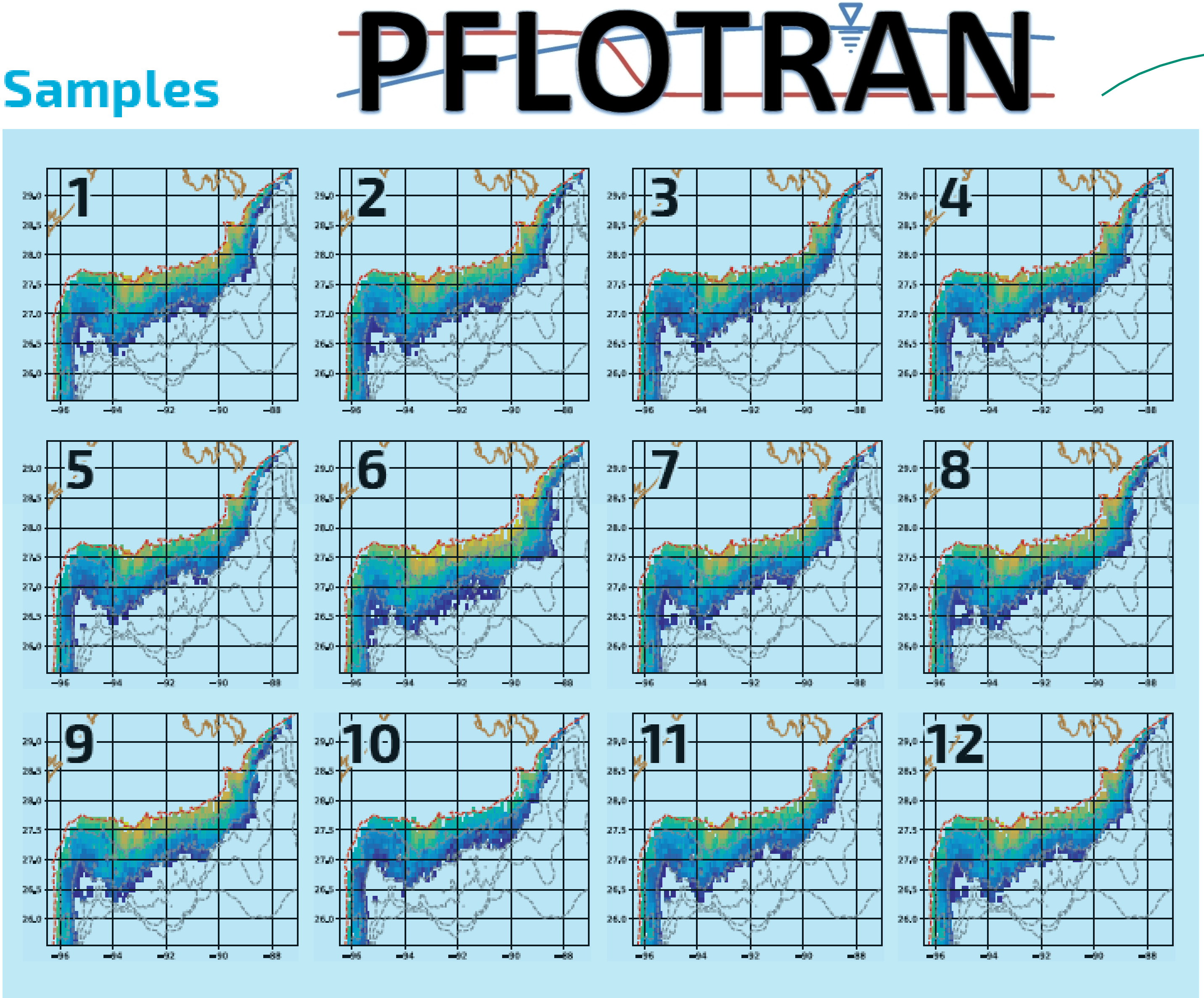
Lee, et al. (2019). Global Biogeochemical Cycles, 33(1), 37-46

DAKOTA
Explore and predict with confidence.

We use DAKOTA to sample on the pdf of each uncertain parameter (here, sedimentation rate and total organic carbon).

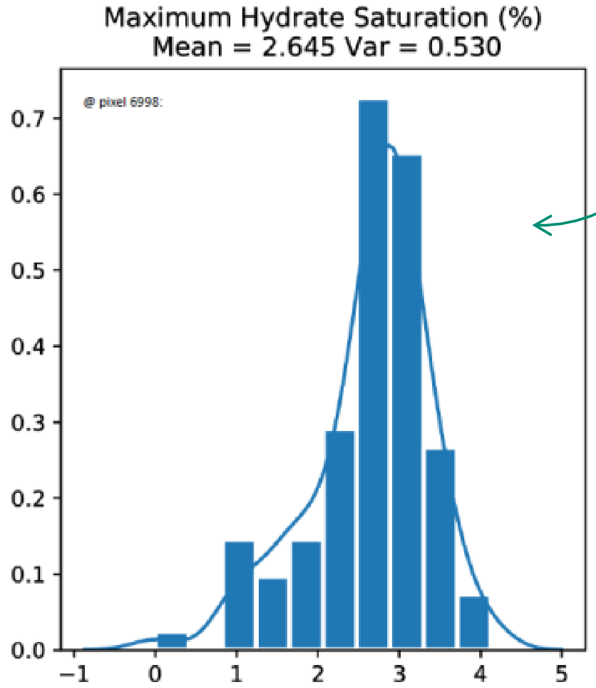
Ensemble Modeling Approach, An Example

Samples

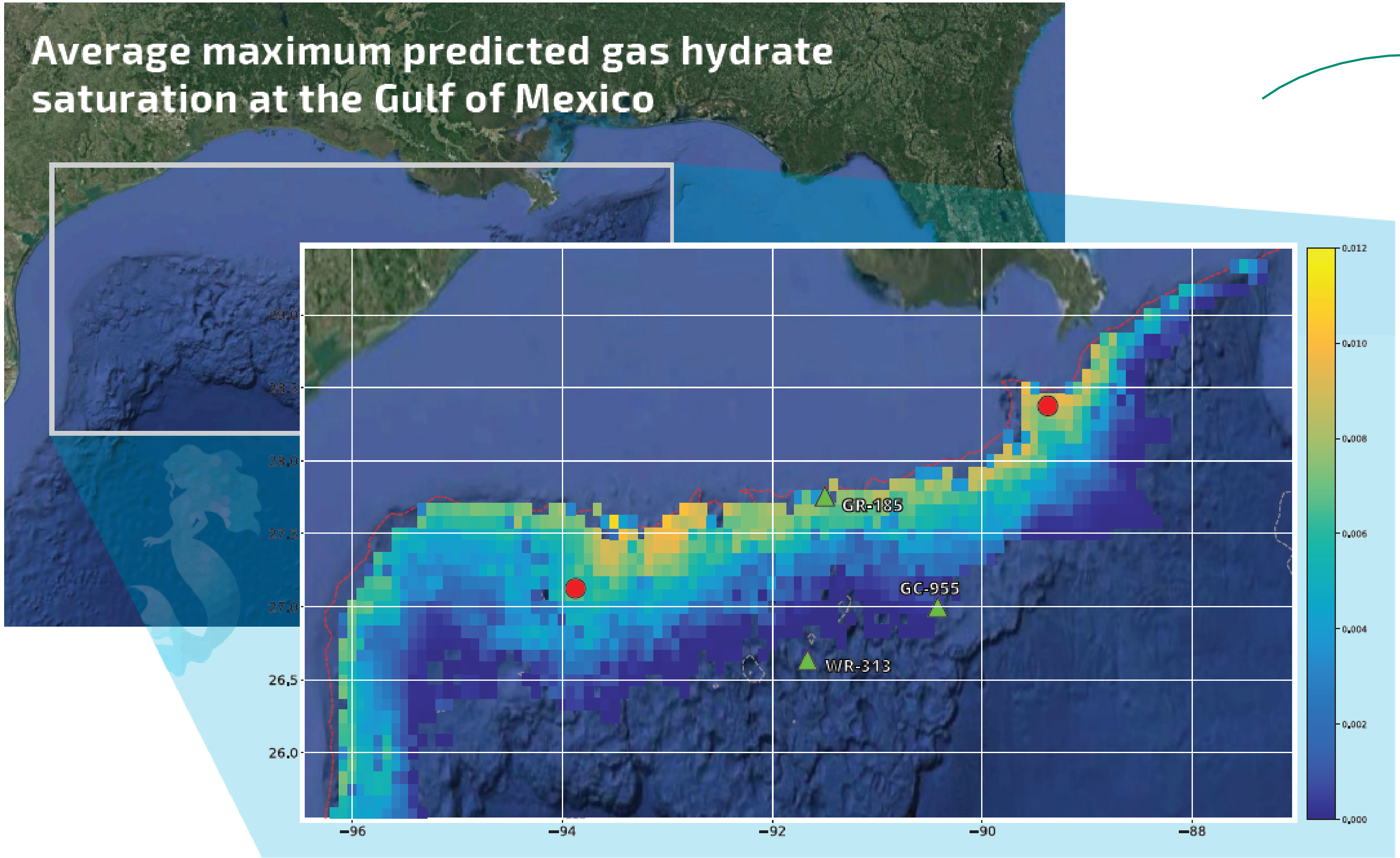


The sampled input parameters define an ensemble of PFLOTRAN (Hydrate Mode) simulations for free gas and gas hydrate distribution (here we show maximum gas hydrate saturation).

Results are compiled into a histogram, and a pdf function is fit:



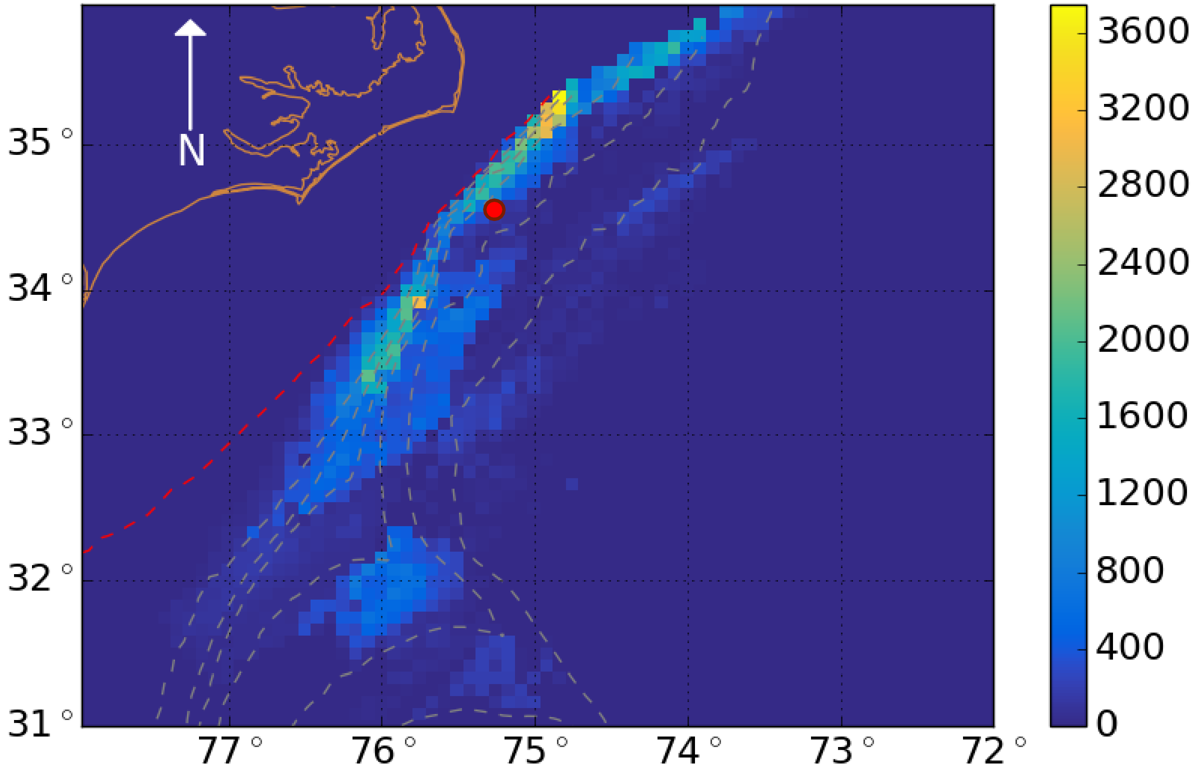
Ensemble Modeling Approach, An Example



A probabilistic map can be created showing the most likely value of your parameter of interest, including uncertainty.

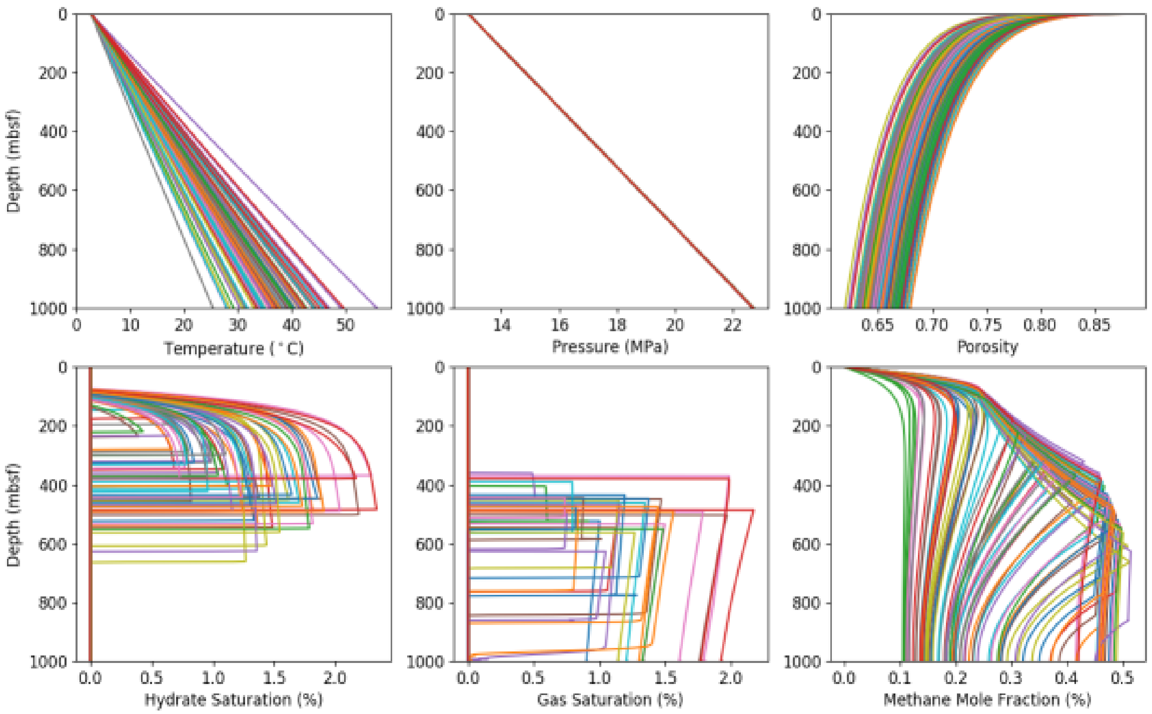
Ensemble Modeling Approach, Another Example

Mass of Hydrate Formation [kg], Most Probable



Probabilistic predictions of gas hydrate formation along the Blake Ridge (left).

Ensemble results at pixel location 7675 (34.625°N, 75.458°W):

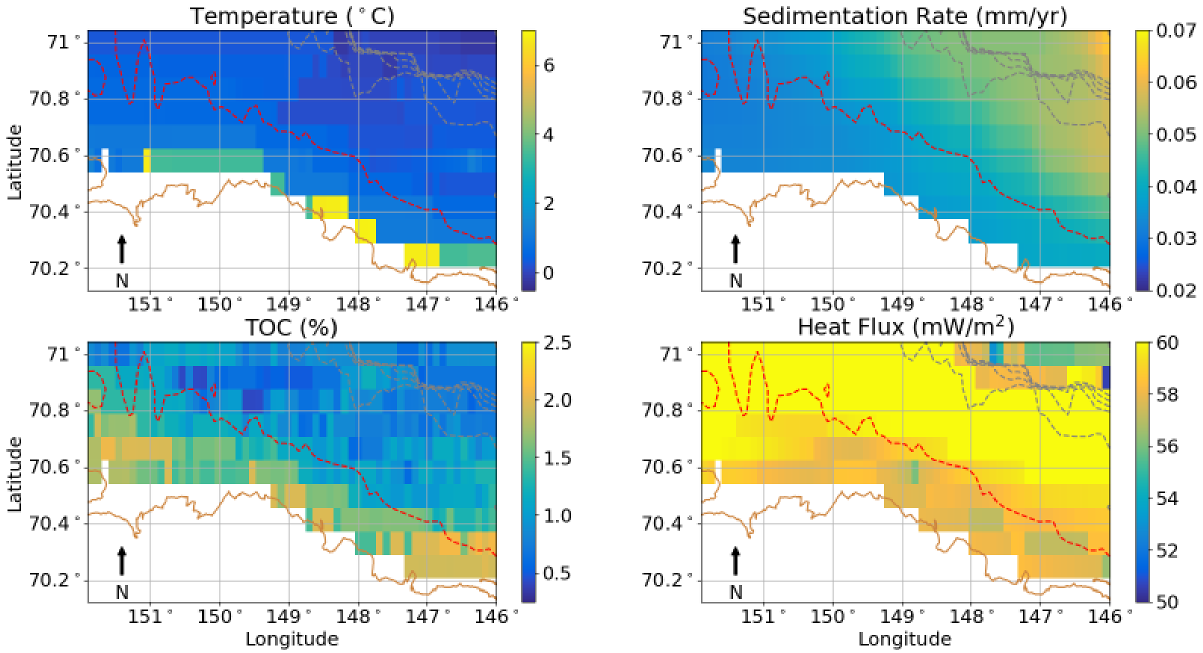


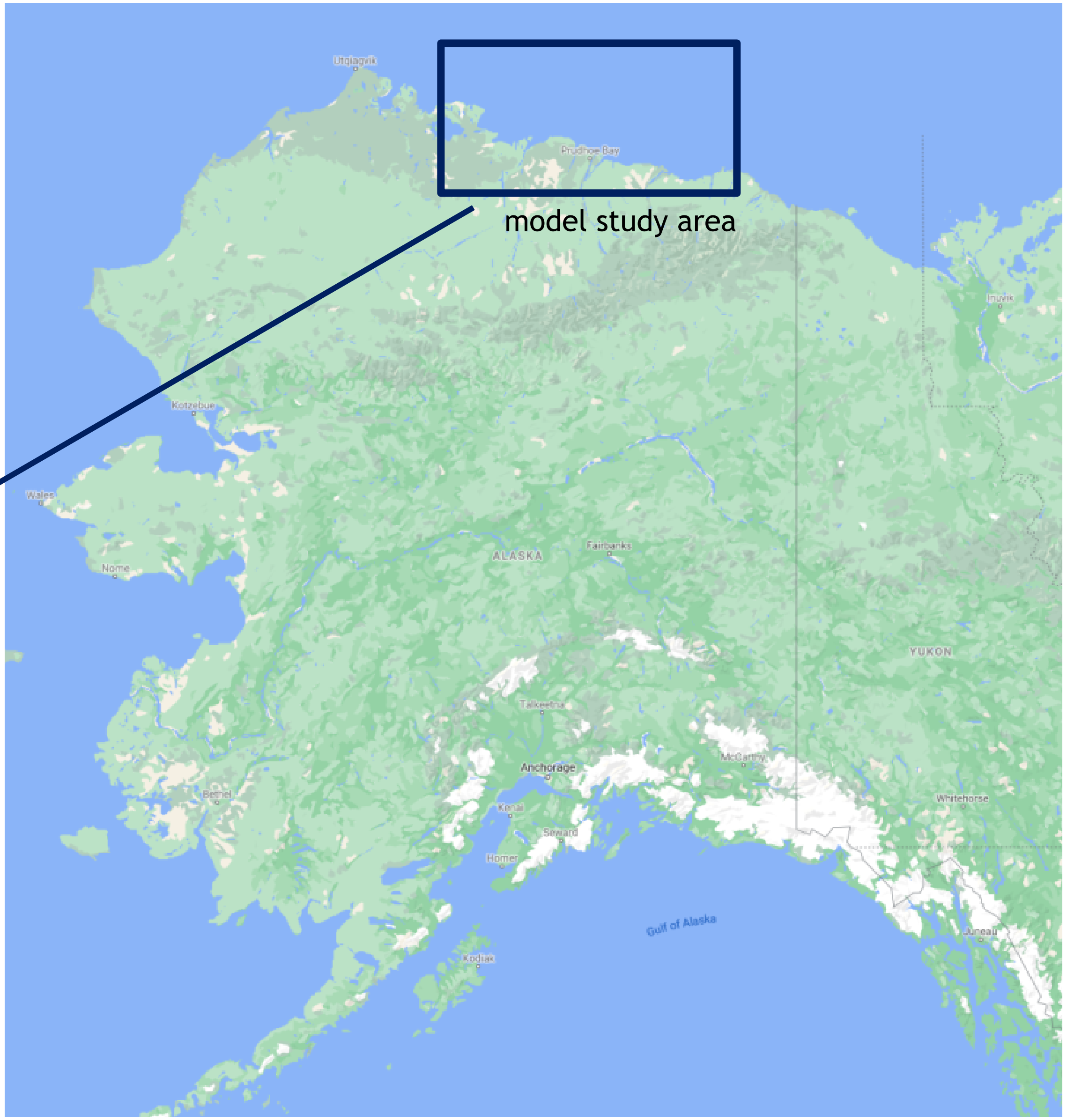
Billy Eymold's PhD dissertation and postdoc research
Eymold et al. (202x), G^3, submitted.

Applying Ensemble Modeling to Predict Arctic Gas Hydrate and Submarine Permafrost Distribution

Can we use our ensemble modeling frame work to predict submarine permafrost distribution?

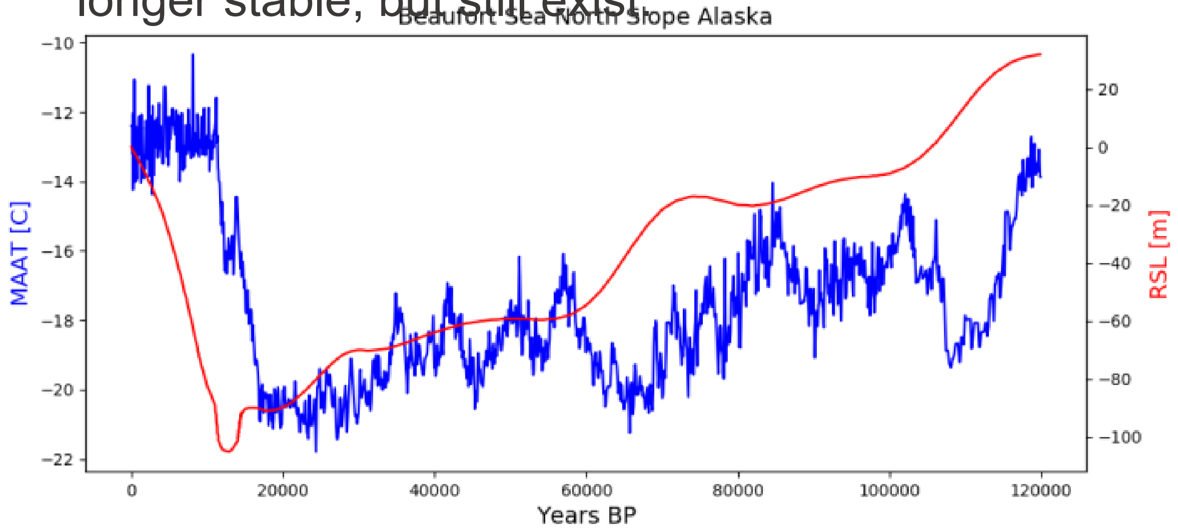
Naval Research Lab's geospatial machine learning maps of input parameters at the North Slope:





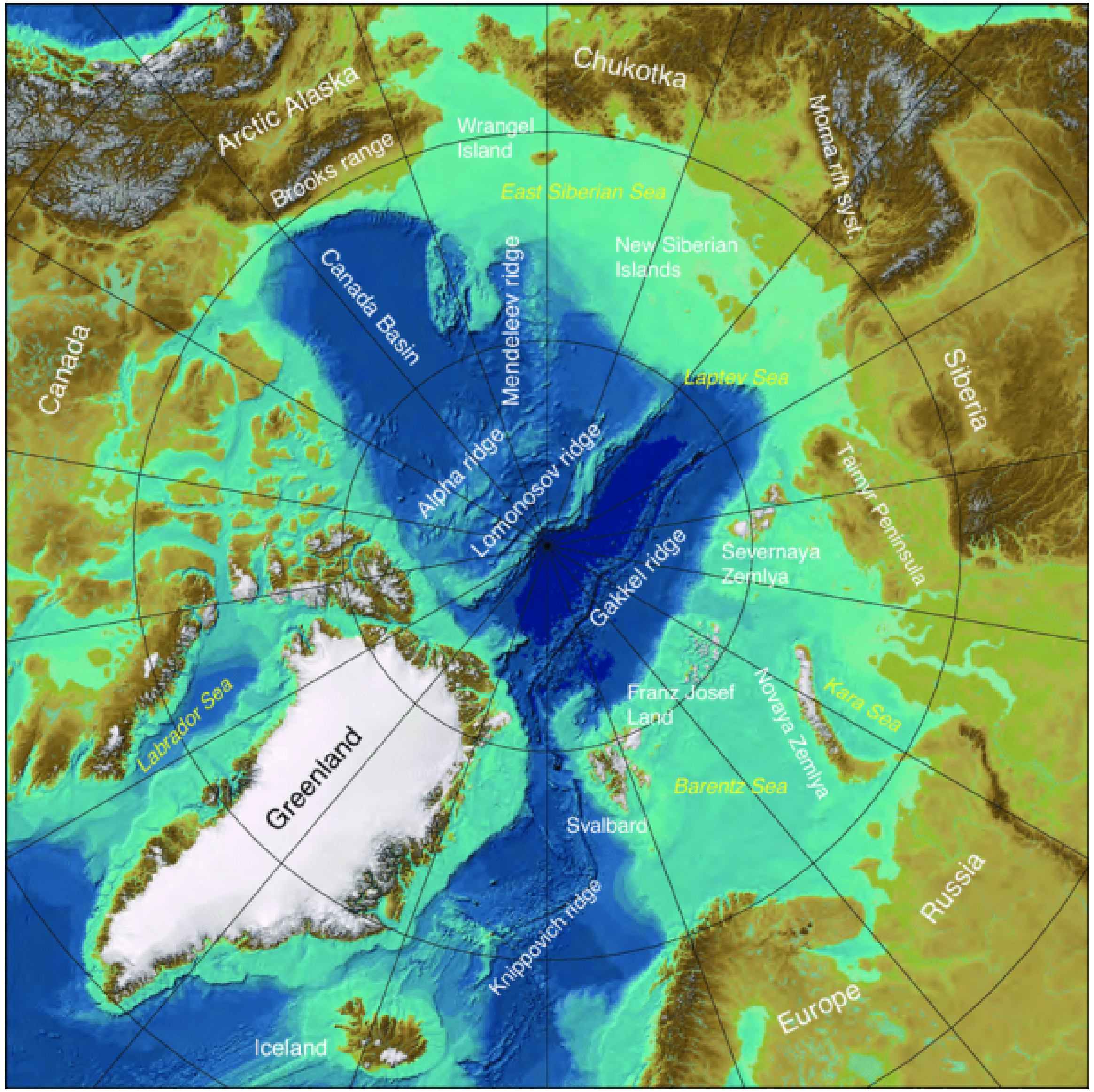
Relict Submarine Permafrost and Gas Hydrate Formation

- During glacial periods, sea level was ~120 m lower than present day, exposing the shallow continental shelves.
- Permafrost and associated gas hydrate formed within the exposed sediments.
- During interglacial periods, ocean transgression submerges the continental shelves, and the submarine permafrost and gas hydrates are no longer stable, but still exist.



Data comes from:
- Petit, J. R., et al. (1999), Climate and atmospheric history of the past 420,000 years from the Vostok Ice Core, Antarctica, Nature, 399, 429-436.
- Zhang, T., T. E. Osterkamp, and K. Stamnes (1996), Some characteristics of the climate in Northern Alaska, U.S.A., Arctic Alpine Res., 28(4), 509-518.
- Peltier, W. R. (2004), Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) Model and GRACE, Annu. Rev. Earth Planet. Sci., 32, 111-149.
- Kendall, R. A., J. X. Mitrovica, and G. A. Milne (2005), On post-glacial sea level—II. Numerical formulation and comparative results on spherically symmetric models, Geophys. J. Int., 161, 679-706.

International Bathymetric Chart of the Arctic Ocean (IBCAO) of Jakobsson et al. (2008)



Previous Studies On Submarine Permafrost Distribution

Brothers, L. L., B. M. Herman, P. E. Hart, and C. D. Ruppel (2016), Subsea ice-bearing permafrost on the U.S. Beaufort Margin: 1. Minimum seaward extent defined from multichannel seismic reflection data, Geochem. Geophys. Geosyst., 17, doi:10.1002/2016GC006584.

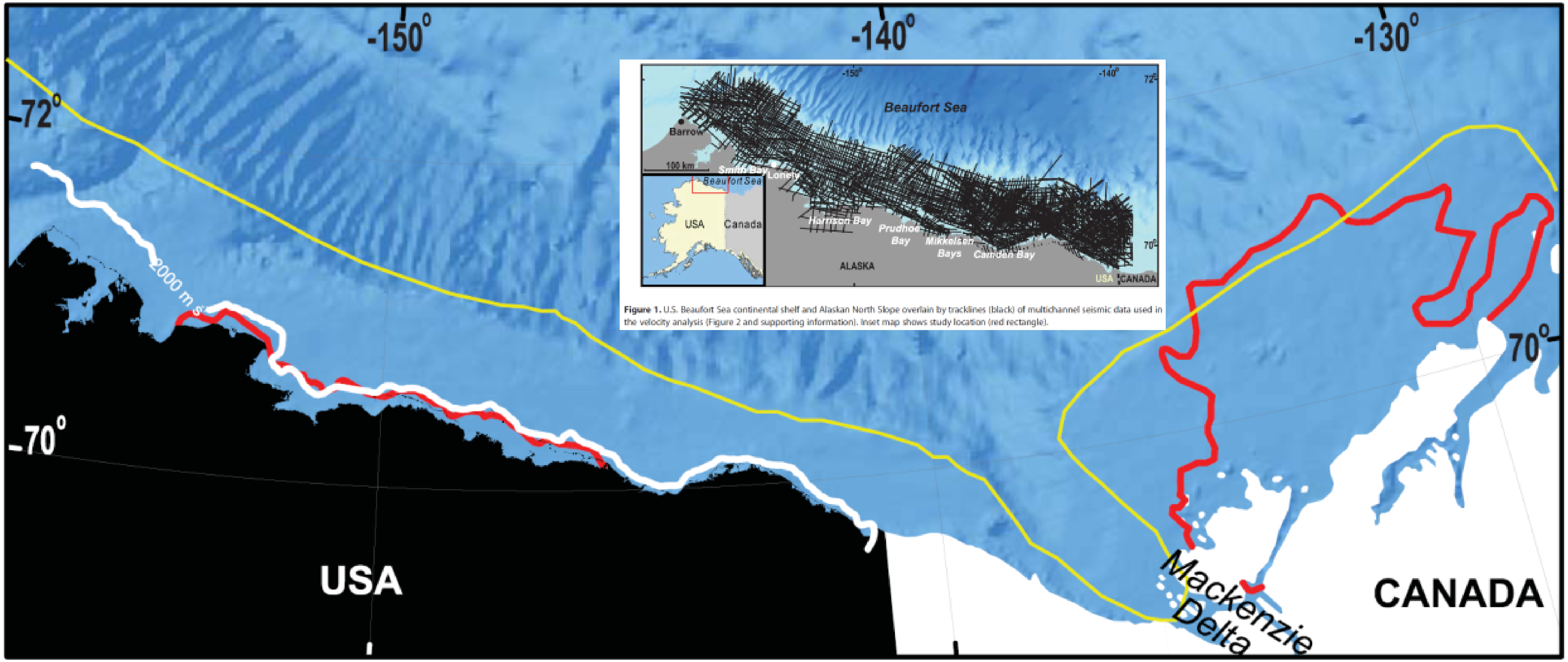
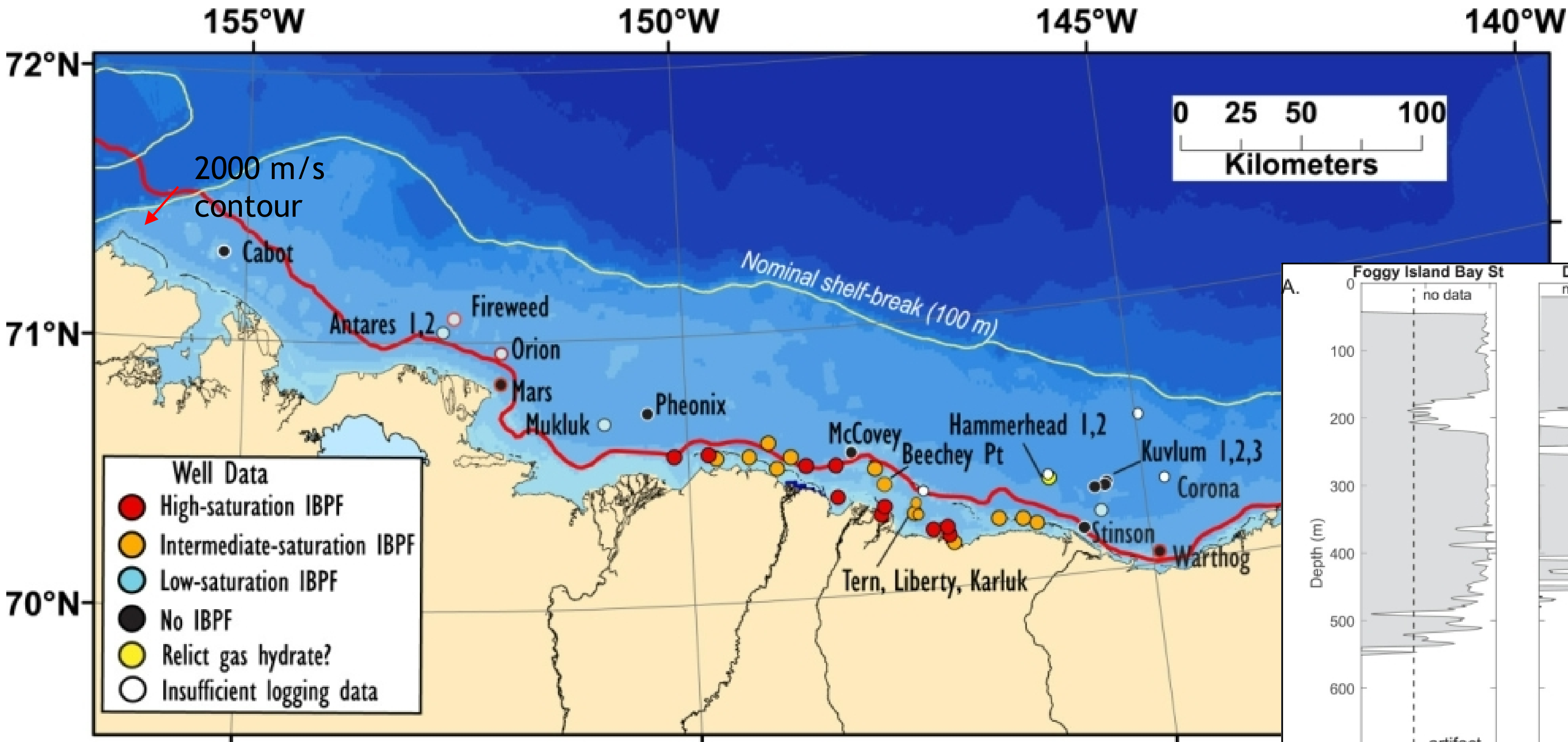


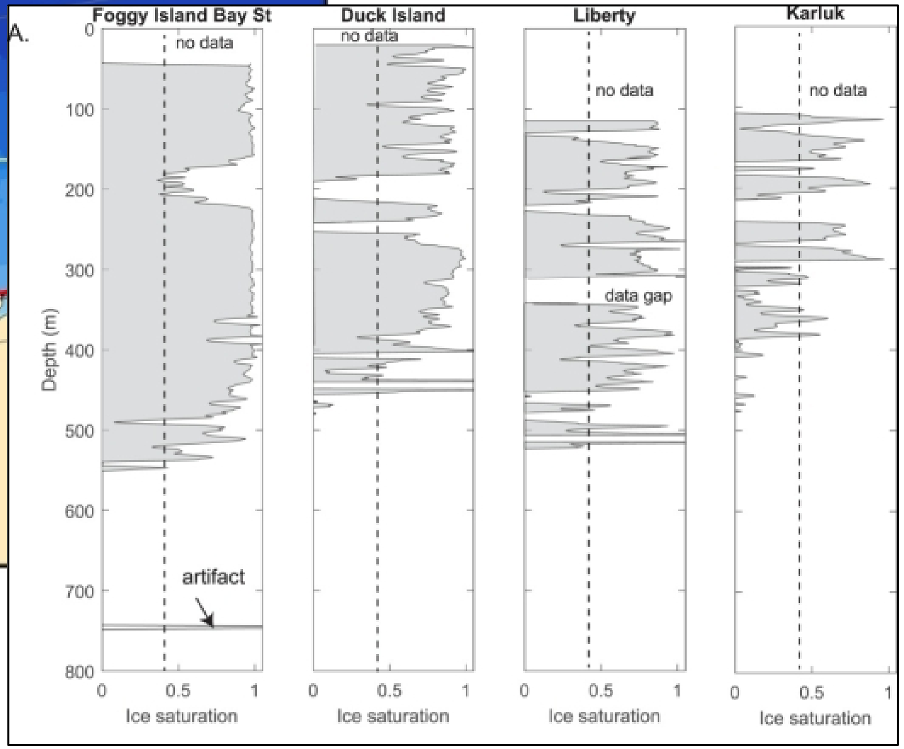
Figure 1. U.S. Beaufort Sea continental shelf and Alaskan North Slope overlain by tracklines (black) of multichannel seismic data used in the velocity analysis (Figure 2 and supporting information). Inset map shows study location (red rectangle).

Figure 6. Map of subsea IBPF indicators on the U.S. & Canadian Beaufort. The yellow line is the proposed near-shelf edge boundary [*Brown et al.*, 1997]. Red lines indicate the seaward extent of subsea permafrost determined by seismic refraction analysis [*Brothers et al.*, 2012; *Hunter et al.*, 1978; *Pullan et al.*, 1987]. White line is the 2000 m s^{-1} contour.

Previous Studies On Submarine Permafrost Distribution

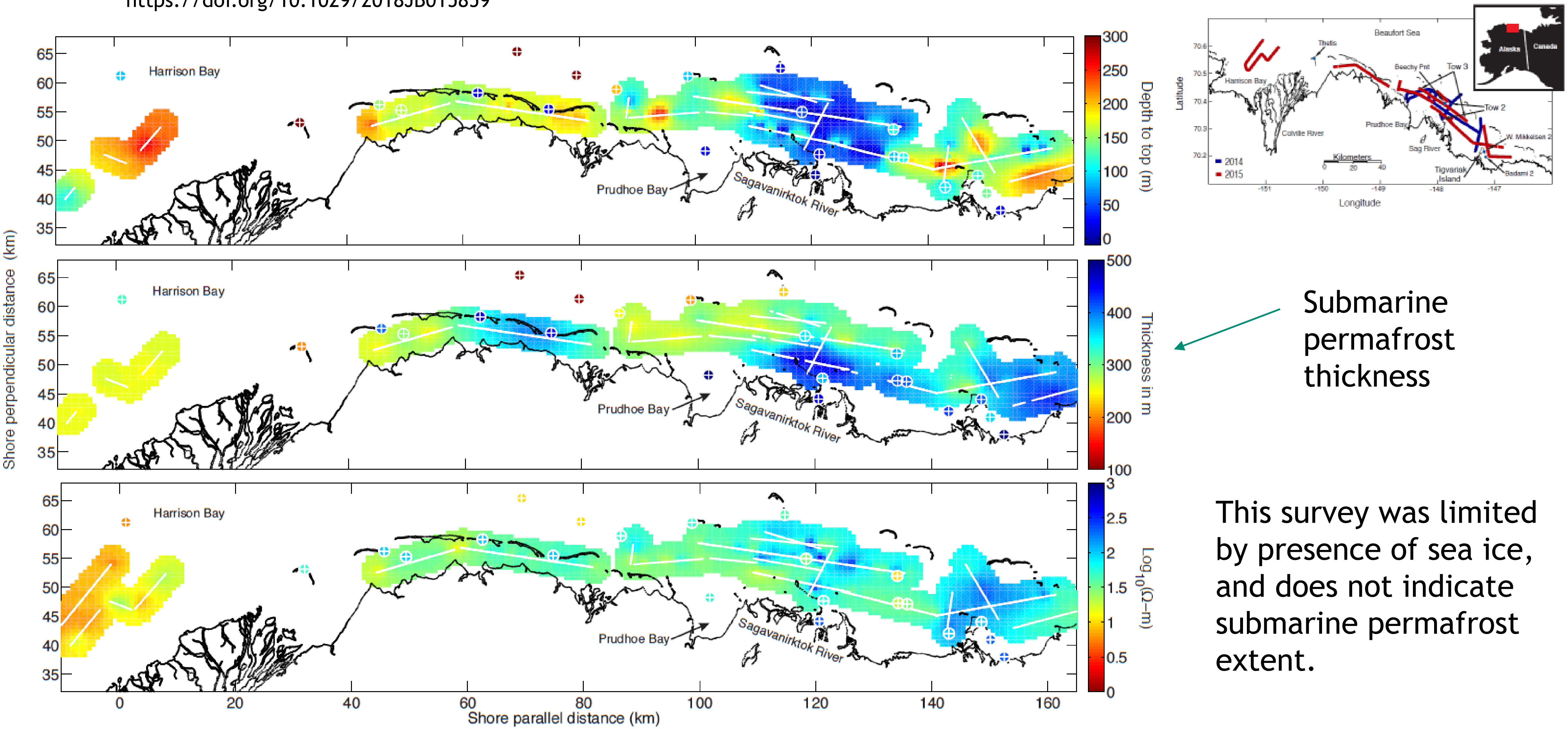
Ruppel, C. D., B. M. Herman, L. L. Brothers, and P. E. Hart (2016), Subsea ice-bearing permafrost on the U.S. Beaufort Margin: 2. Borehole constraints, Geochem. Geophys. Geosyst., 17, 4333–4353, doi:10.1002/2016GC006582.





Previous Studies On Submarine Permafrost Distribution

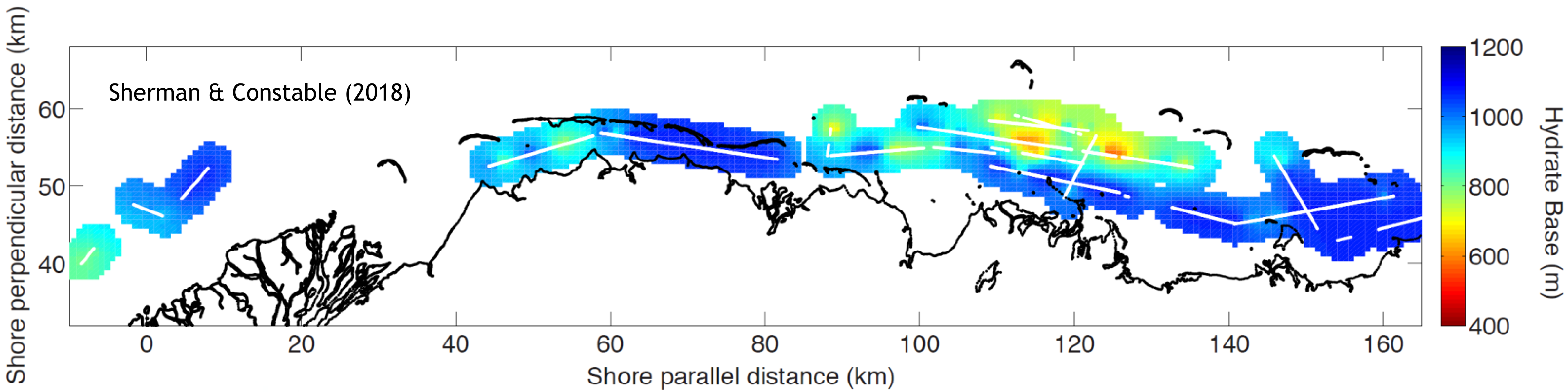
Sherman, D., & Constable, S. (2018). Permafrost extent on the Alaskan Beaufort shelf from surface-towed controlled-source electromagnetic surveys. Journal of Geophysical Research: Solid Earth, 123, 7253–7265. https://doi.org/10.1029/2018JB015859

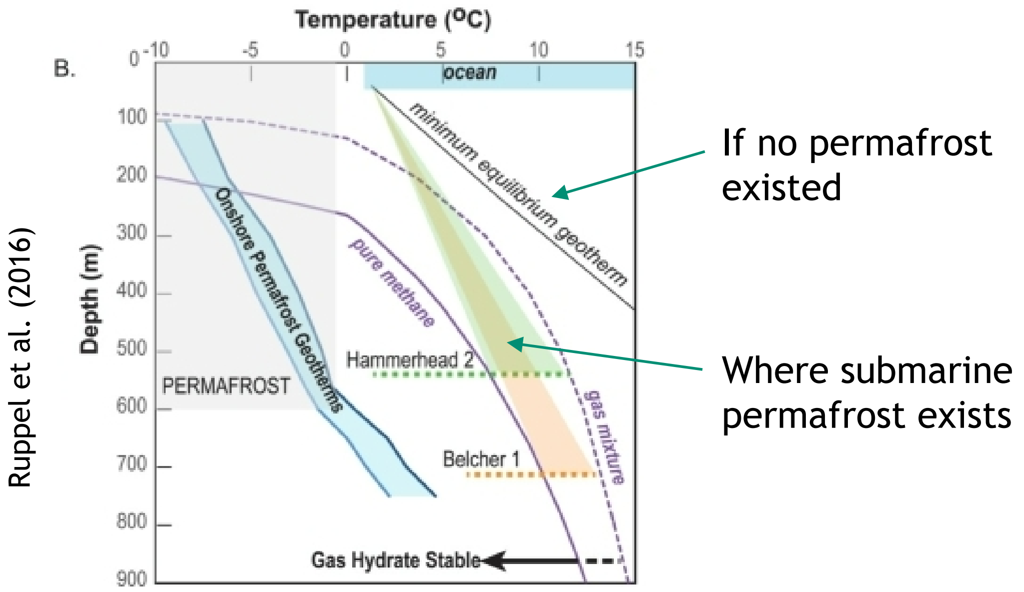


Submarine permafrost thickness

This survey was limited by presence of sea ice, and does not indicate submarine permafrost extent.

Submarine Permafrost Implies Gas Hydrate Stability





- Permafrost and associated gas hydrate likely formed simultaneously within the exposed sediments during glacial epochs.
- At present day, the thermal input required to thaw submarine permafrost has kept sediment temperatures low enough to maintain gas hydrate stability where submarine permafrost still exists.

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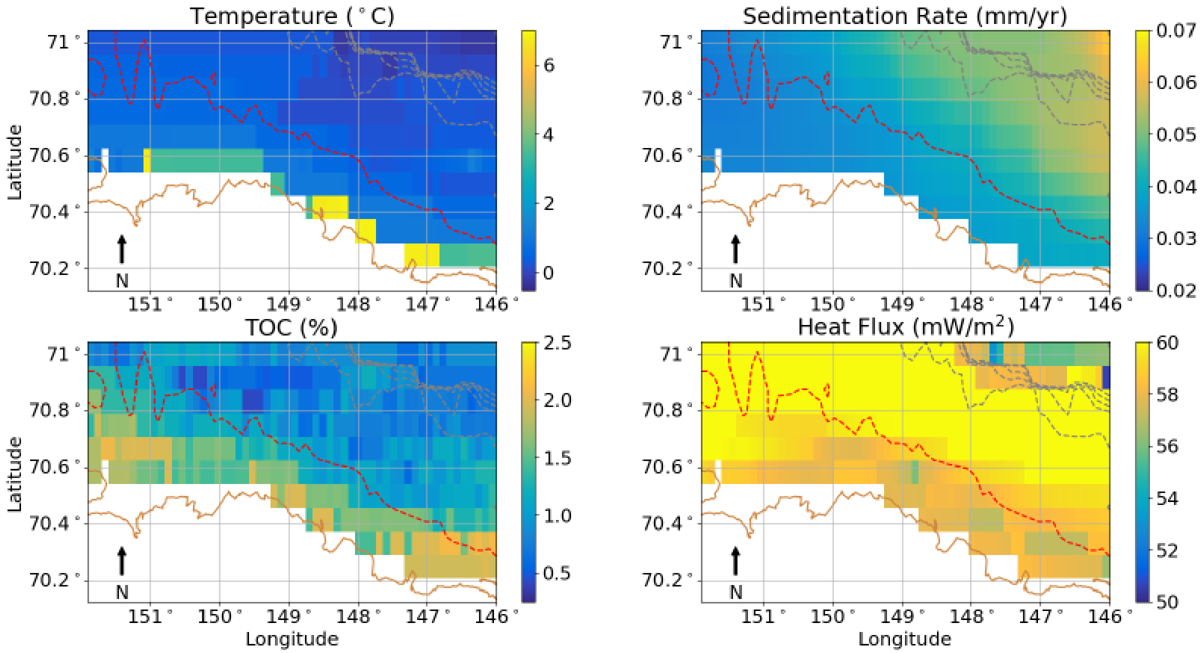
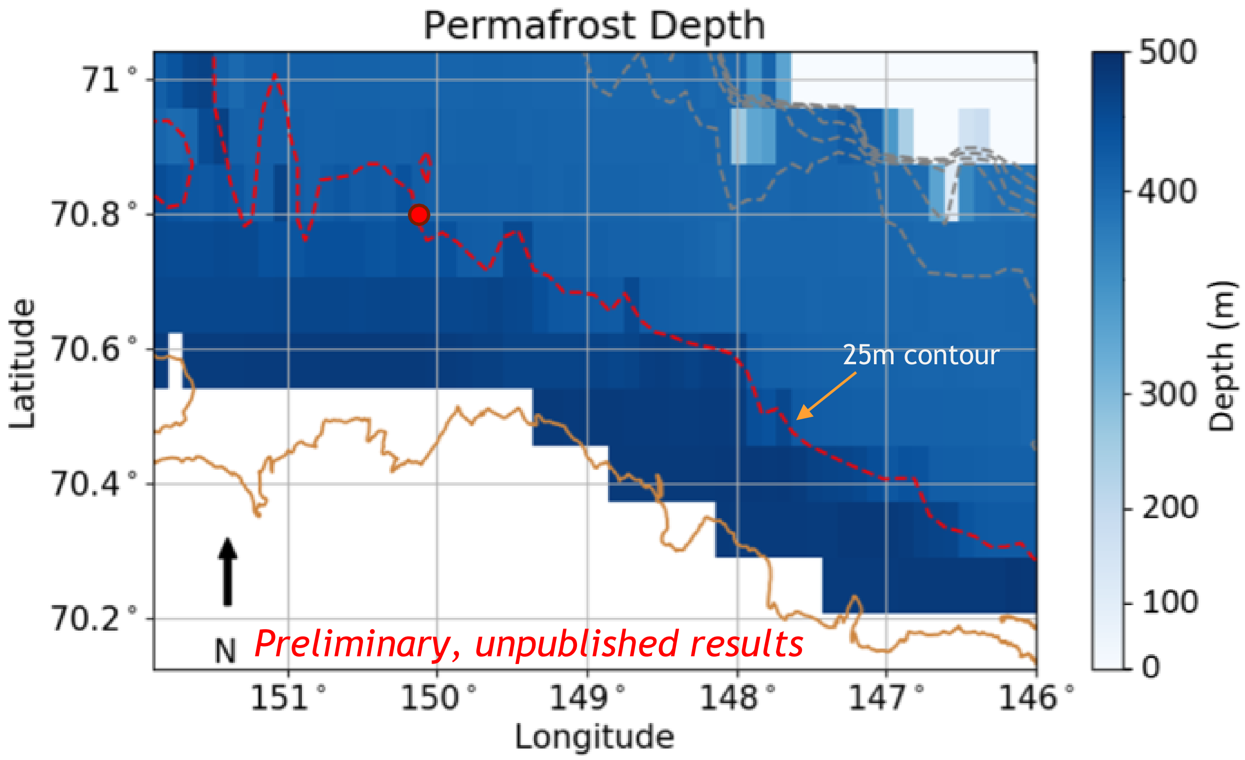
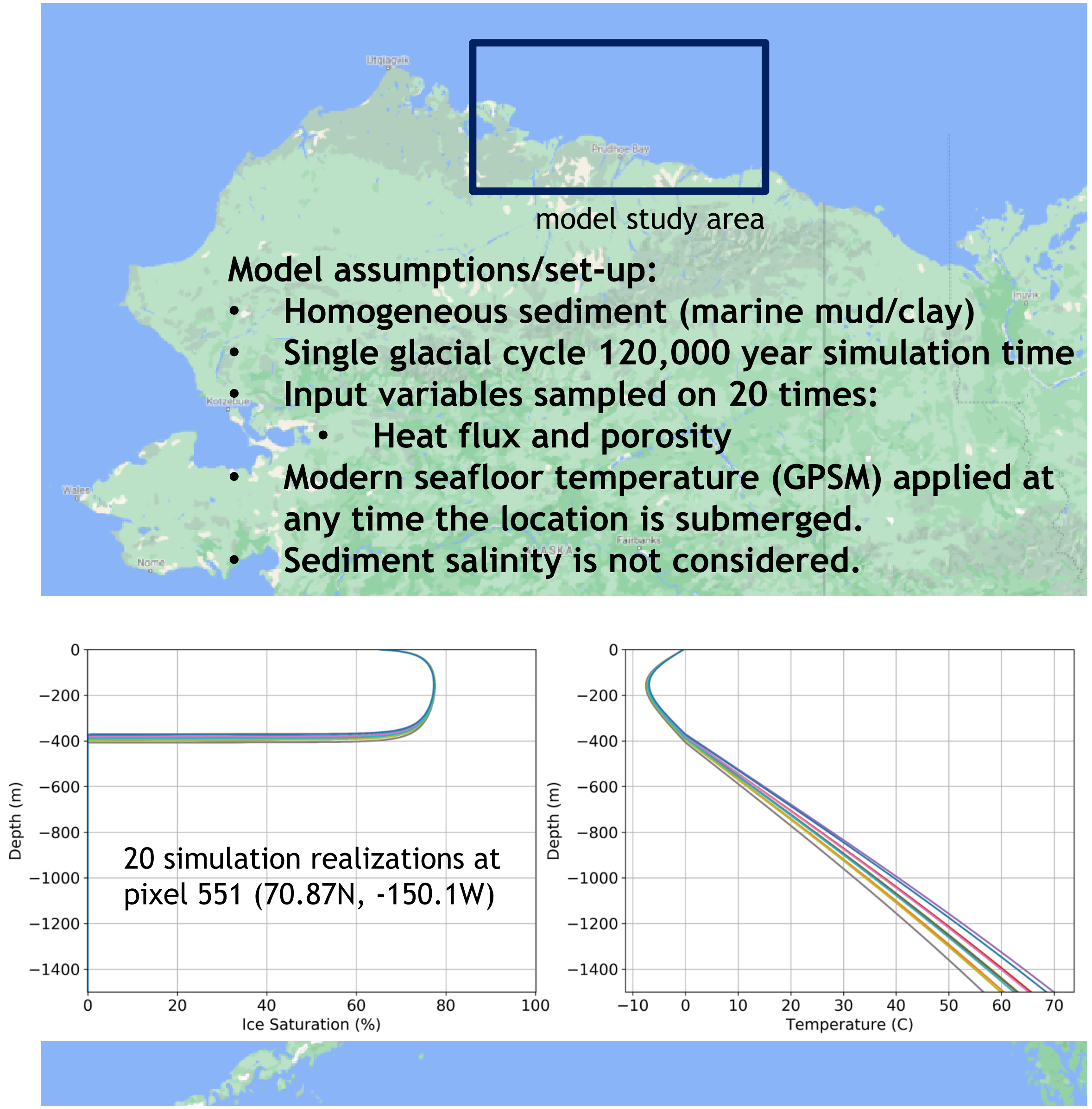


Applying Ensemble Modeling to Predict Arctic Gas Hydrate and Submarine Permafrost Distribution

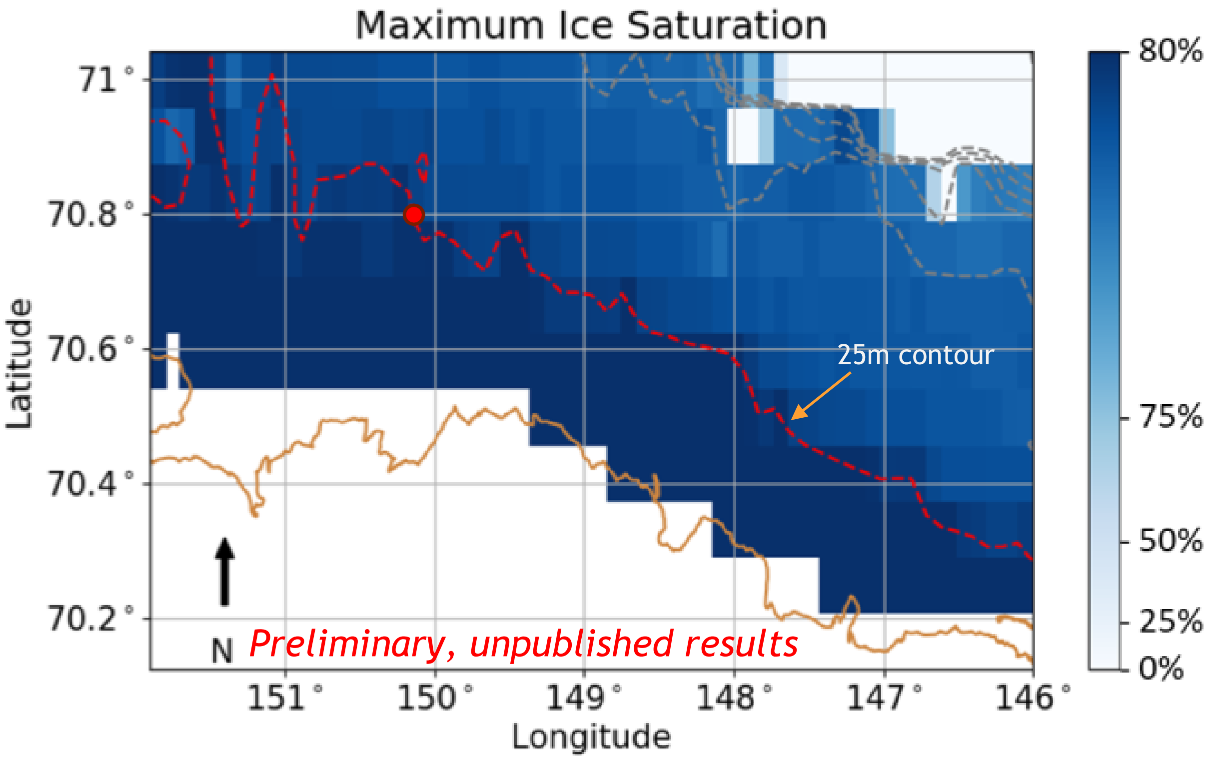
- Extensive submarine permafrost is predicted with a thickness 300 – 500 m.
  - Model results predict permafrost out to shelf edge, which is inconsistent with previous observations, which limit permafrost to ~ 30km offshore.
  - Implies sea level curve or sediment characteristics need improvement.

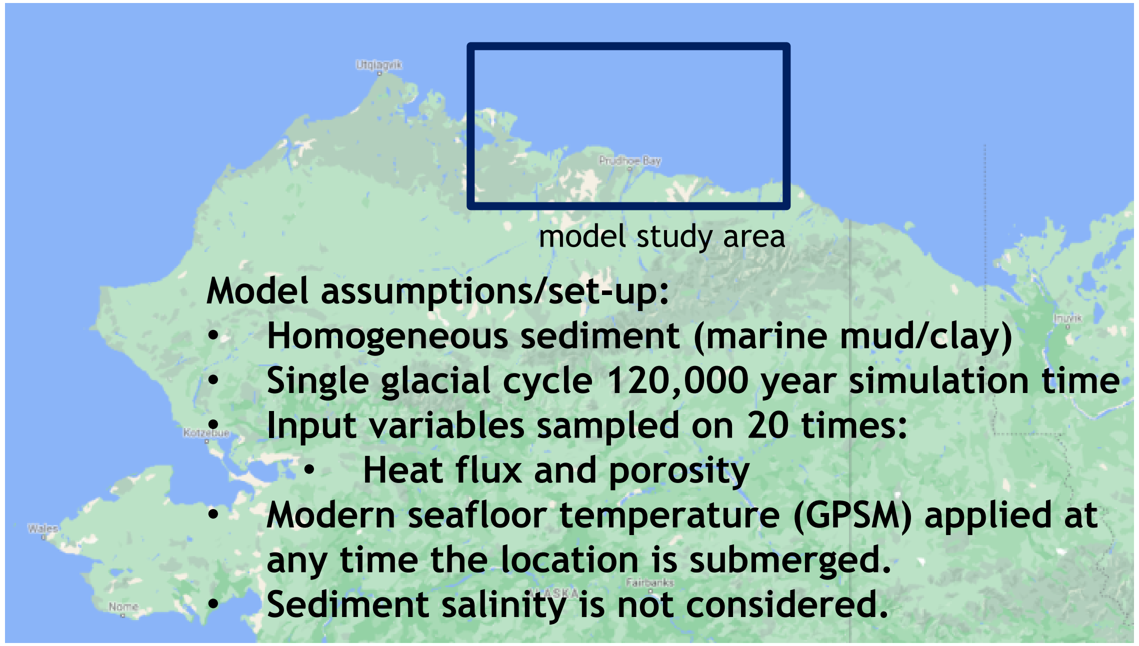




Applying Ensemble Modeling to Predict Arctic Gas Hydrate and Submarine Permafrost Distribution

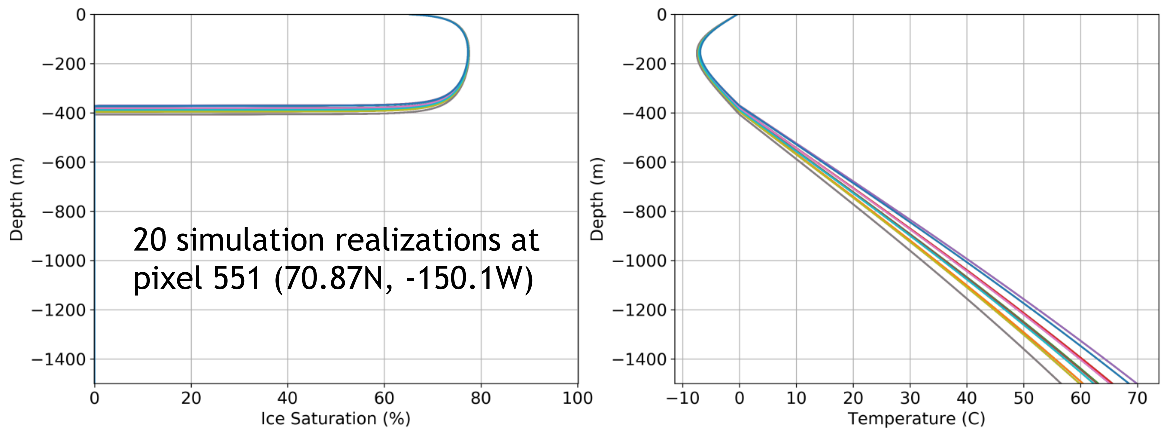
- Submarine permafrost has high ice saturation.
  - Model results are consistent with borehole observations near-shore, but over predict ice content towards shelf edge.
  - Implies sea level curve or sediment characteristics need improvement.

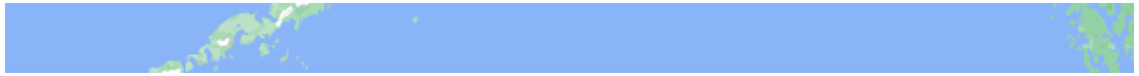




Model assumptions/set-up:

- Homogeneous sediment (marine mud/clay)
- Single glacial cycle 120,000 year simulation time
- Input variables sampled on 20 times:
  - Heat flux and porosity
- Modern seafloor temperature (GPSM) applied at any time the location is submerged.
- Sediment salinity is not considered.





Applying Ensemble Modeling to Predict Arctic Gas Hydrate and Submarine Permafrost Distribution

- Future Work:
  - Incorporate effects of salinity in submarine permafrost ice model.
  - Include spatial variation in sediment properties.
  - Add gas hydrate model to PFLOTRAN ensemble simulations.
    - Produce probabilistic maps of free gas and gas hydrate distribution on North Slope.

Thank you for your interest. Please don’t hesitate to contact me with questions via e-mail: jmfrede@sandia.gov

Jenn