Thermokarst-On-Demand:

Observations from a Controlled Permafrost Warming Experiment

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Poster #T-6

Abstract

Thermokarst modifies landscape, reroutes surface and groundwater flow, changes vegetation, increases wildfire susceptibility, and releases carbon dioxide and methane to the atmosphere. Understanding the physics of the thermokarst lifecycle – from incipient thaw to catastrophic drainage – is complicated by coupled thermal, hydrological, and mechanical feedbacks. Models representing how suprapermafrost zones evolve above degrading permafrost are limited by a lack of real-world observation. This project aims to calibrate existing thermokarst models through a controlled-warming experiment in Fairbanks, Alaska. During August – October 2016, we used 122 60-W vertical resistive heaters to ablate a 4-4.5m-deep, 140 m^2 permafrost table by about 1 m, which resulted in as much as 10 cm of subsidence in some areas. A dense array of traditional and distributed fiber optic sensors captured different components of the thaw process at this interface. Surface and vertical slim-hole temperature sensors (thermocouples and fiber optic distributed temperature sensing) were installed above and below the permafrost table to measure the thermal evolution of the suprapermafrost-permafrost interface. Electronic Distance Measurement (EDM), GPS, time-lapse photogrammetry, LiDAR, and fiber optic distributed strain sensing recorded the deforming surface topography. Passive ambient vehicular traffic and a surface orbital vibrator (SOV) active source were recorded by geophone, broadband, and fiber optic distributed acoustic sensing instruments, enabling measurement of changes in relative shear wave speed and dispersive surface wave propagation. Using this multifaceted dataset, we examine the timing and velocity of the suprapermafrost-permafrost interface as a consequence of heat transport, and examine the coupling between thermal erosion and mechanical deformation.

The Suprapermafrost-Permafrost Interface

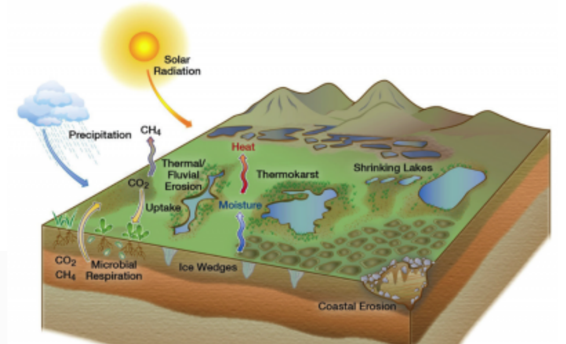
Vocabulary

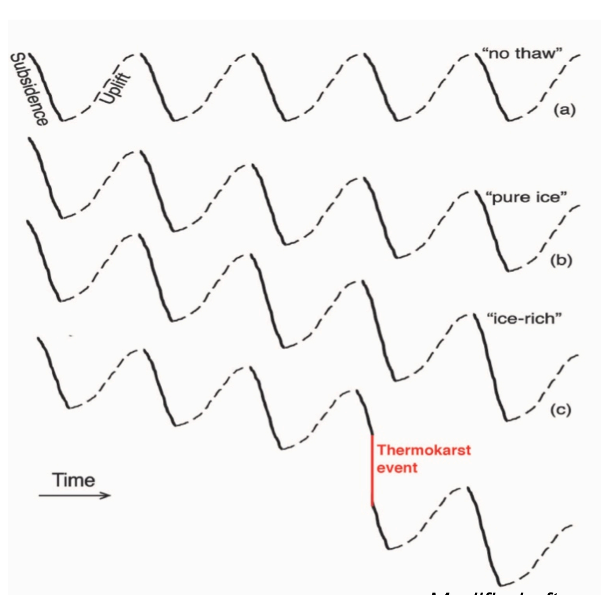
Permafrost (n.) : 1. Frozen soil and ground ice; 2. Subsurface with a mean annual temperature <0 °C for at least two consecutive years.

Suprapermafrost (n.) : The unfrozen zone above permafrost (below the active layer).

Thermokarst (n., v.): The landform and process name of melting ground ice and the consequent subsidence and formation of surface depressions and taliks.

1. Permafrost thaw is both a response to and a driver of change in Earth's climate. Because global climate change is preferentially warming high latitudes, the UN Environmental Program has identified permafrost thaw as one of the most significant yet least studied environmental hazards.



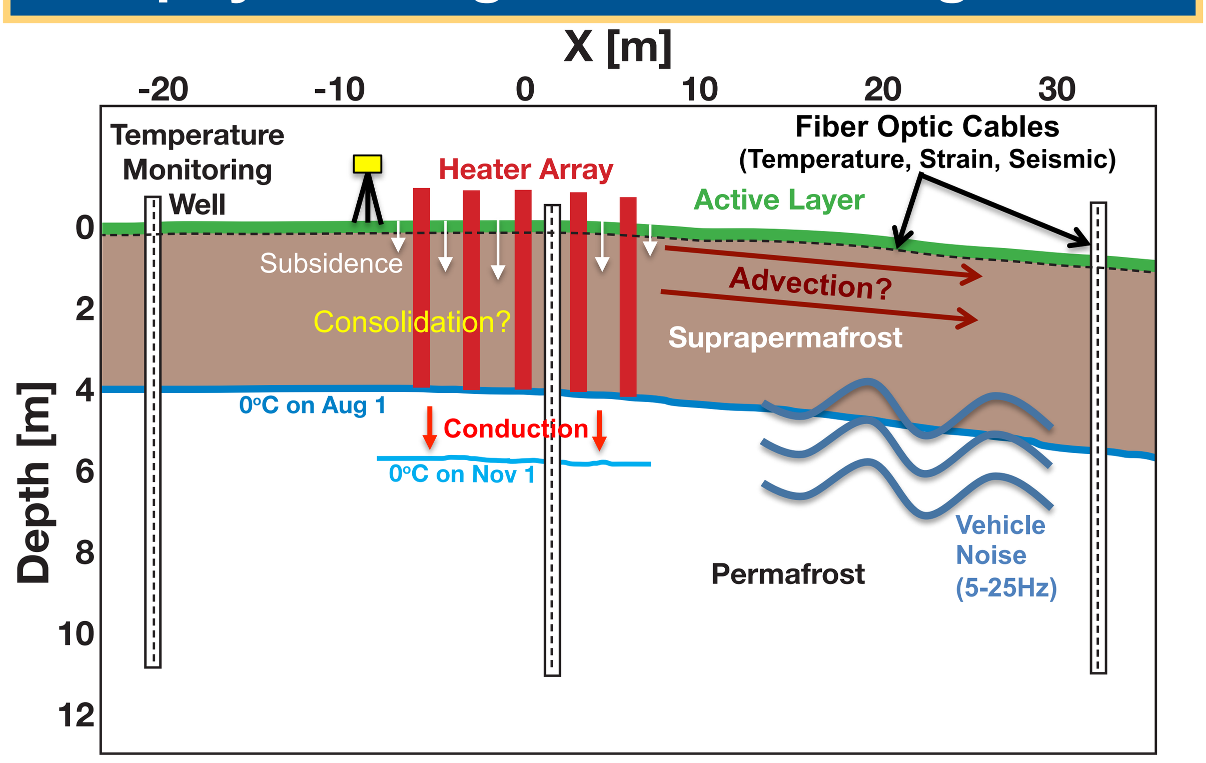


Modified after Liu et al., (2016)

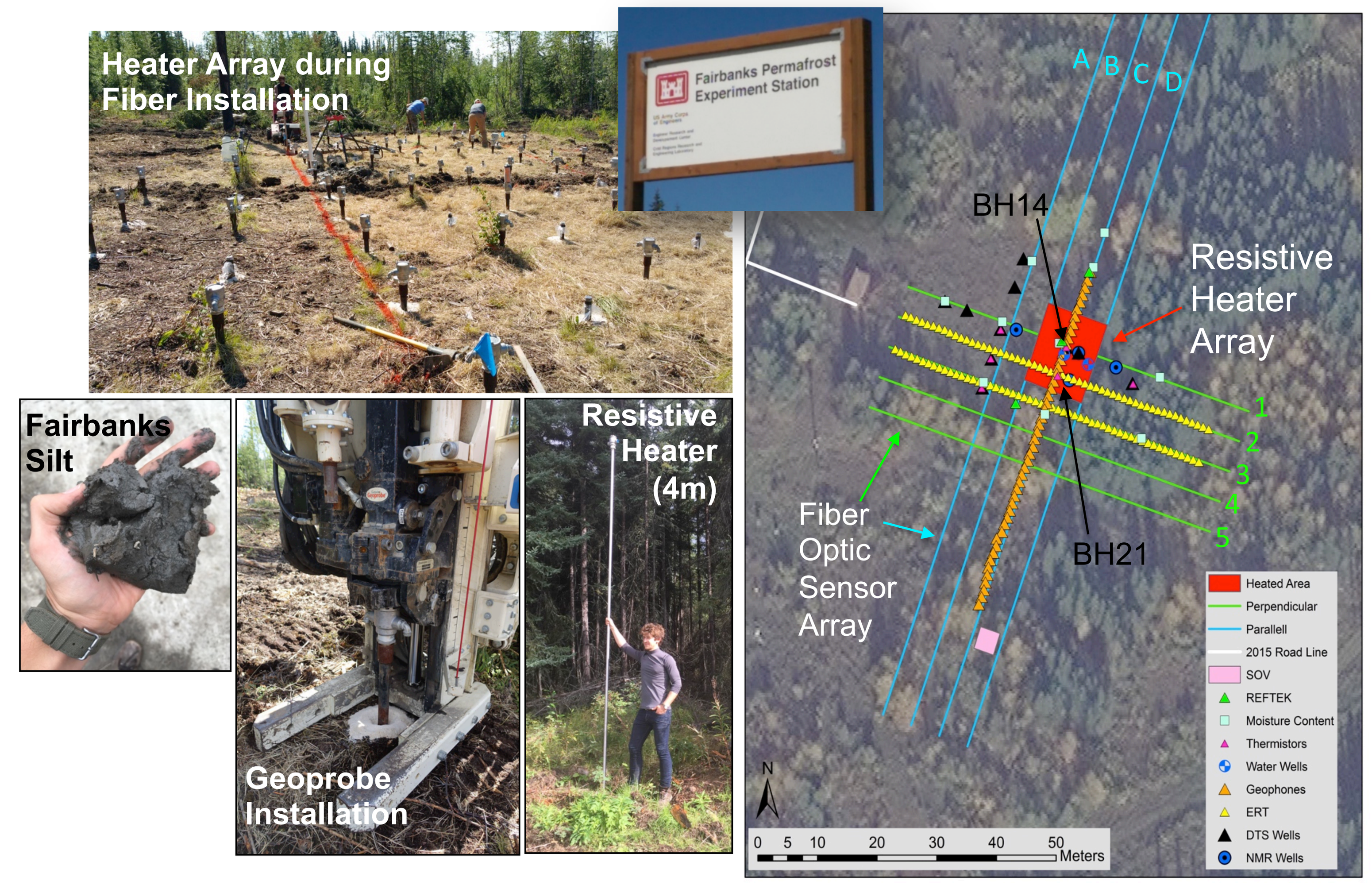
2. The thermal, hydrological, and mechanical physics of permafrost thaw have been hypothesized to couple in complicated ways, but data collection efforts to study these feedbacks in the field have been limited in range and/or resolution in both time and space. As a result, lab and numerical models largely outpace important field calibration datasets.

3. Understanding the thermokarst lifecycle – from incipient thaw, through the variable modes of subsidence, to eventual talik development or drainage – begins with understanding the available geophysical signals that could be used to probe the coupled THM physics of the suprapermafrost-permafrost interface.

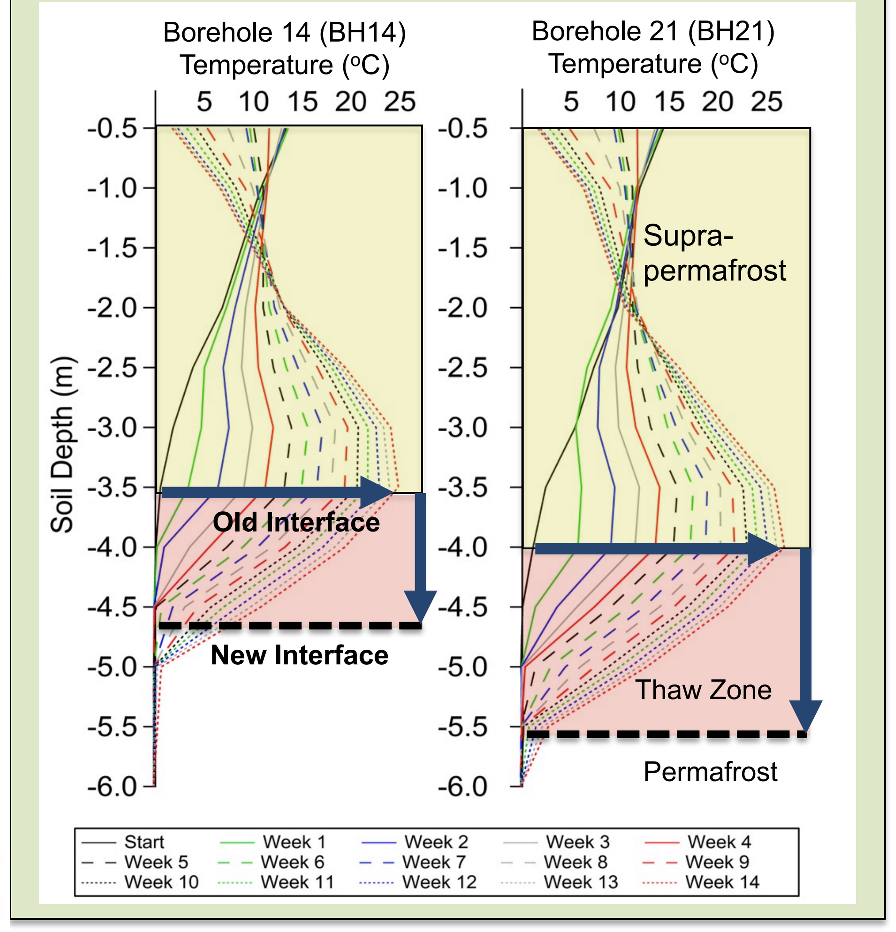
Geophysical Signals of Warming



Inducing Thaw at the Suprapermafrost-Permafrost Interface

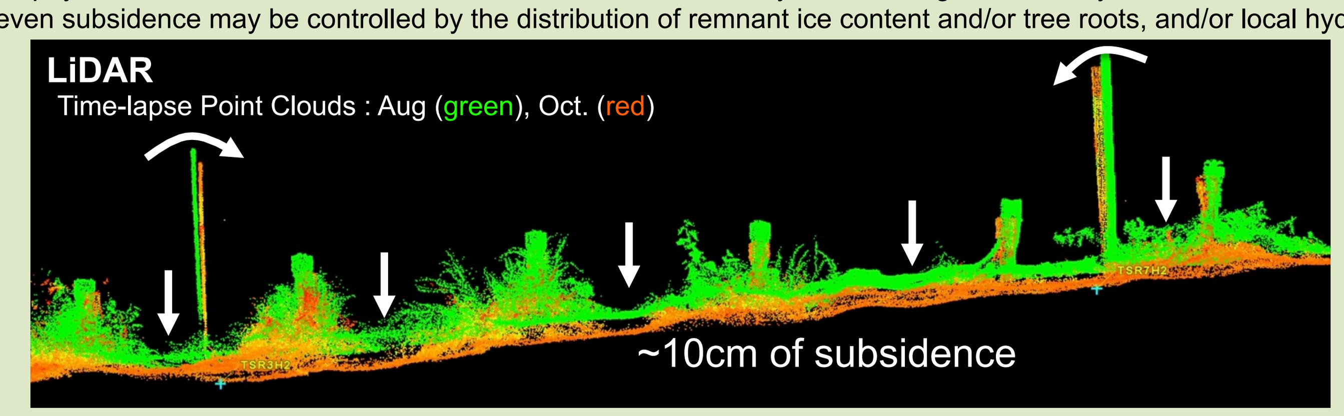


Thermal Response of Interface to Warming



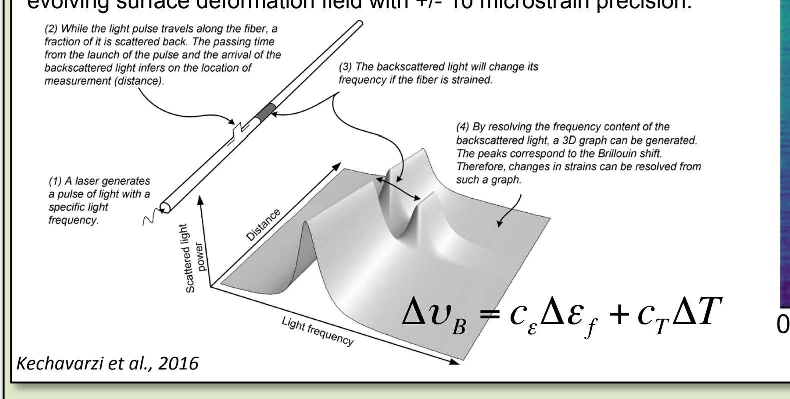
Surface Deformation

Multiple geophysical methods observe ~10cm of subsidence after 56 days of warming, with an asymmetric concentration to the north. Uneven subsidence may be controlled by the distribution of remnant ice content and/or tree roots, and/or local hydrology.

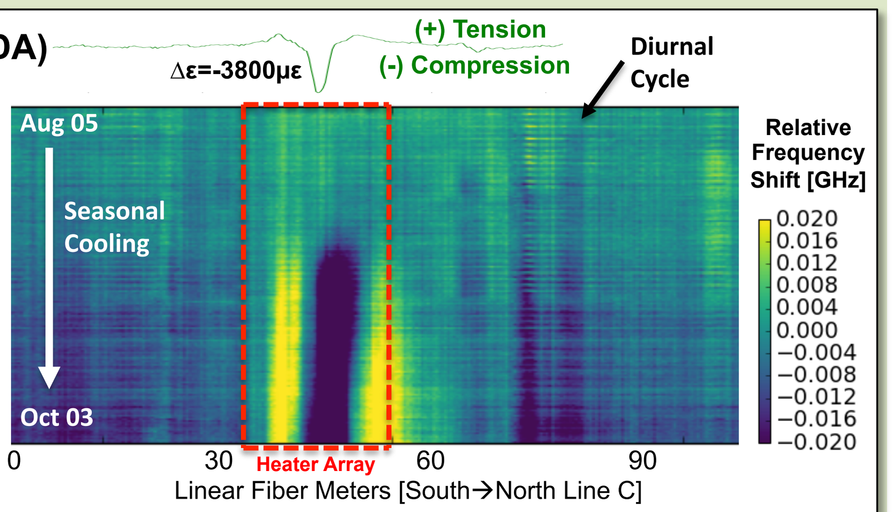


Distributed Fiber Optic Strain Sensing (BOTDA)

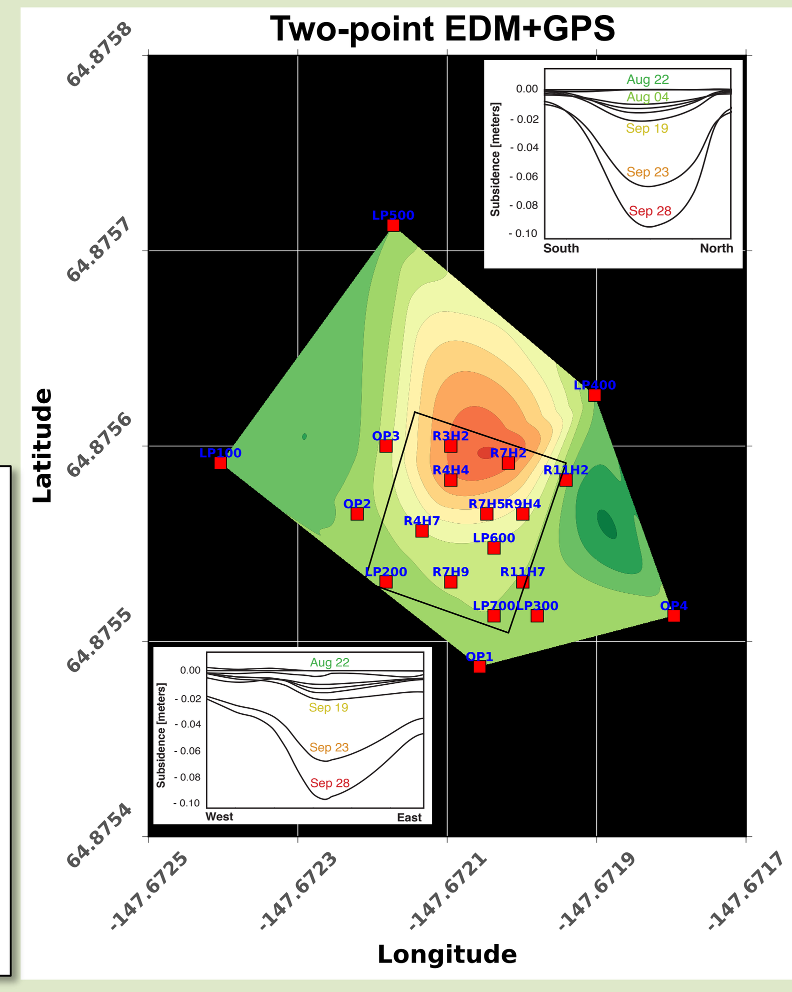
Continuous measurements of the Brillouin frequency shift (GHz) at 25 cm increments over the fiber array provide dense observation of the evolving surface deformation field with +/- 10 microstrain precision.



Kechavarzi et al., 2016



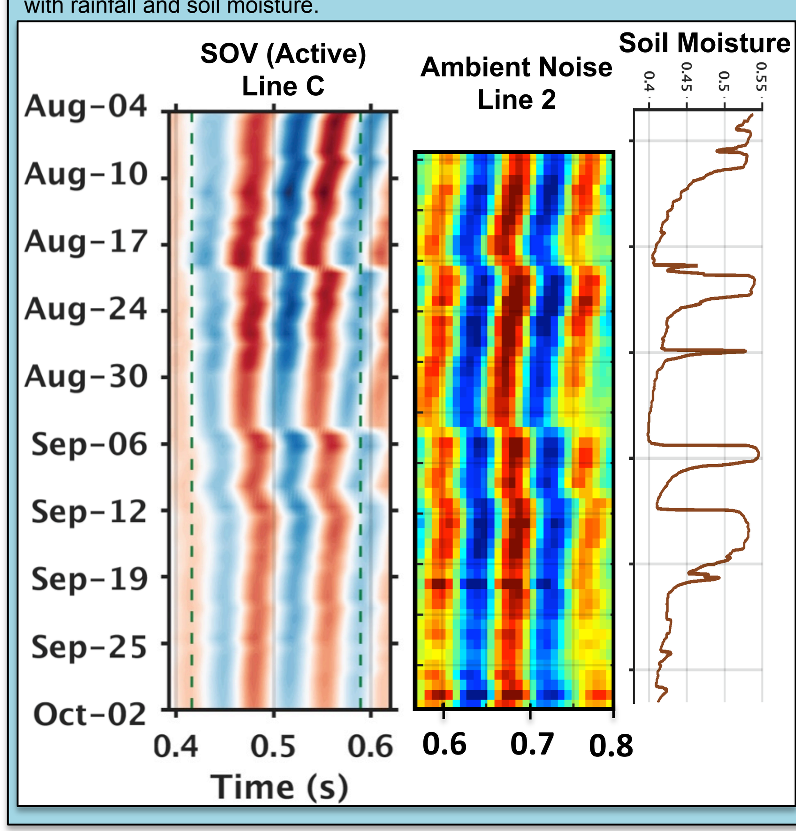
Two-point EDM+GPS



Time-lapse Active and Passive Seismology with Large-N Distributed Fiber Optic Sensors

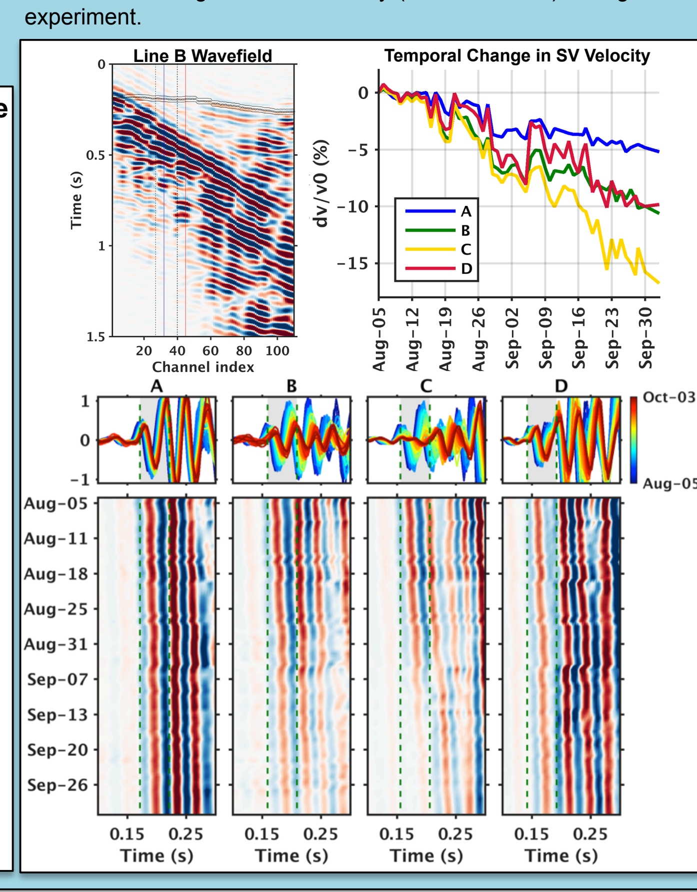
Rayleigh Wave Group Velocity Changes

Surface waves generated by both a repeating active source and retrieved from a nearby road using an ambient noise workflow are used to investigate potential shear-wave velocity changes due to thaw. Inline DAS components show a dominant <12% dv/v change that directly correlates with rainfall and soil moisture.



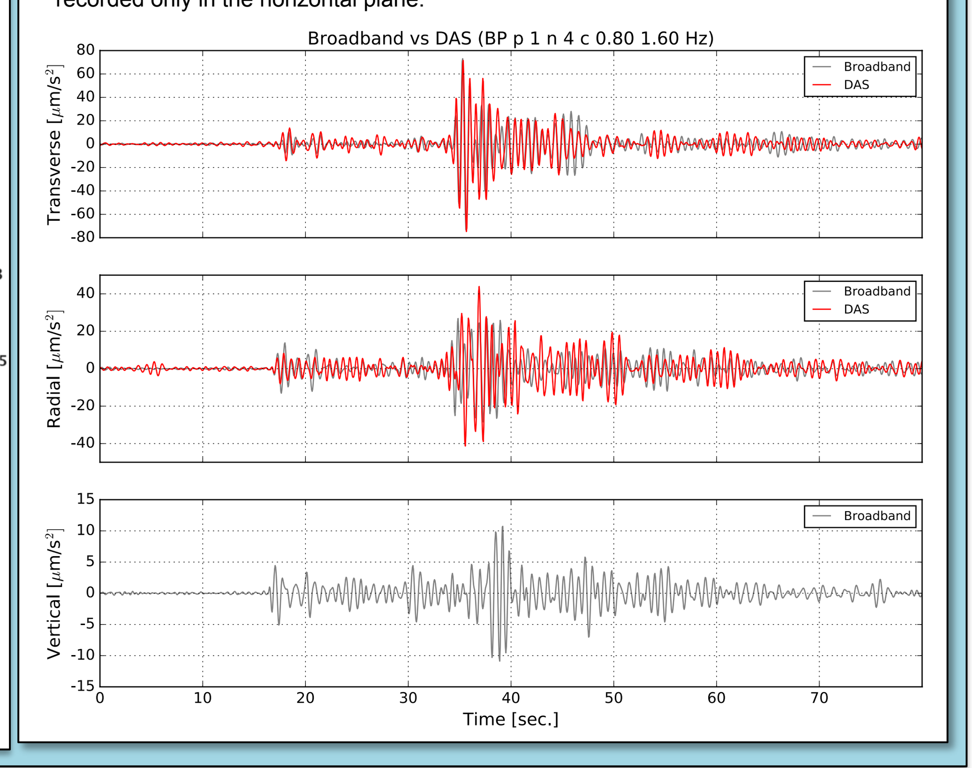
SV Refraction with an active source

Refracted arrivals show indication of gradual slow down and attenuation through the heater array (Lines B and C) during the experiment.



Can fiber optics accurately measure ground motion?

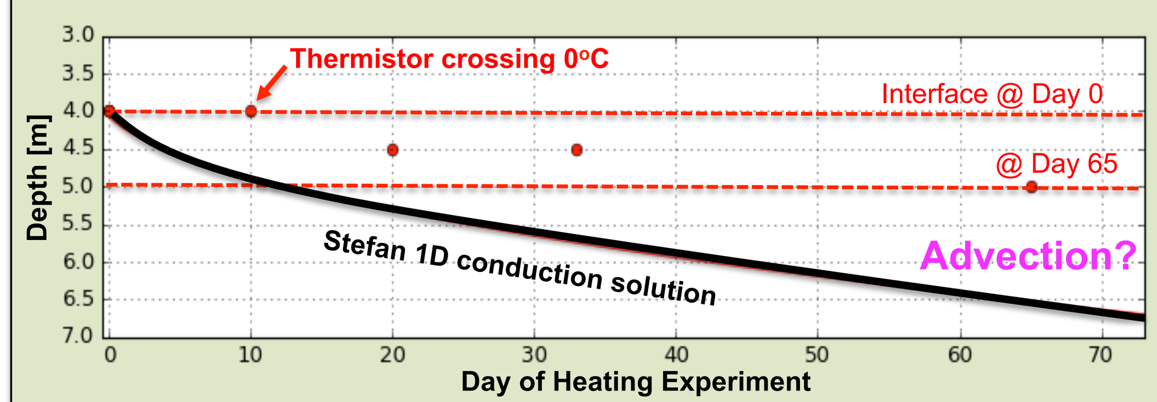
DAS sensitivity for a 20m stack (1 channel/m) is found to be nearly equivalent to a high-quality broadband seismometer in the frequency band of interest for shallow Earth imaging. Using a 3C broadband seismometer (Nanometrics Trillium PC 120s) installed on the heater array, we compare estimates of earthquake ground motion emanating from Central Alaska (2016-08-26 M3.8,~150km south). The DAS is recorded only in the horizontal plane.



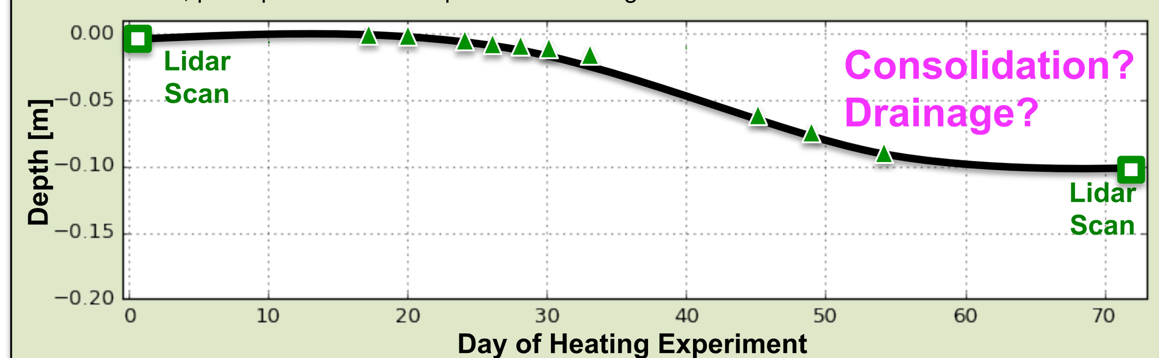
Discussion

Suprapermafrost-Permafrost Interface Dynamics

Conduction dominates when permeability is too low to permit faster thermal transport. Modeling the suprapermafrost-permafrost boundary as a 1-D Stefan problem (pure conduction) using measurements of heat input and starting temperatures predicts about 3 m of top-down thaw, but only 1.0 – 1.5 m. Lateral advection of heat downslope may explain this disparity.



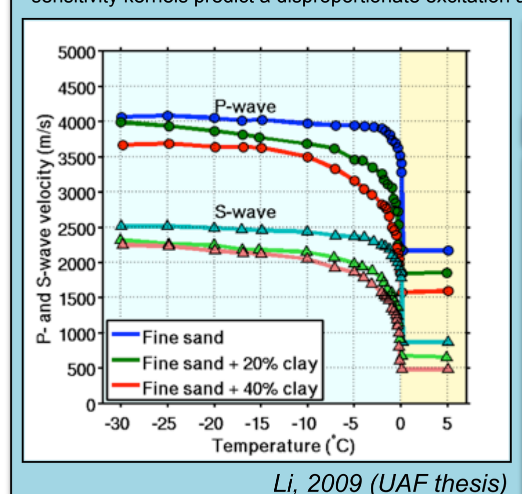
Subsidence was observed from Day 20 with the maximum rate of subsidence occurred around Day 45. Water's solid-liquid phase change explains 9% of the volume loss or 4 cm of the vertical subsidence for an initial ice content of 40%. Additional subsidence (~6 cm) may be due to soil consolidation, perhaps connected to pore fluid drainage.



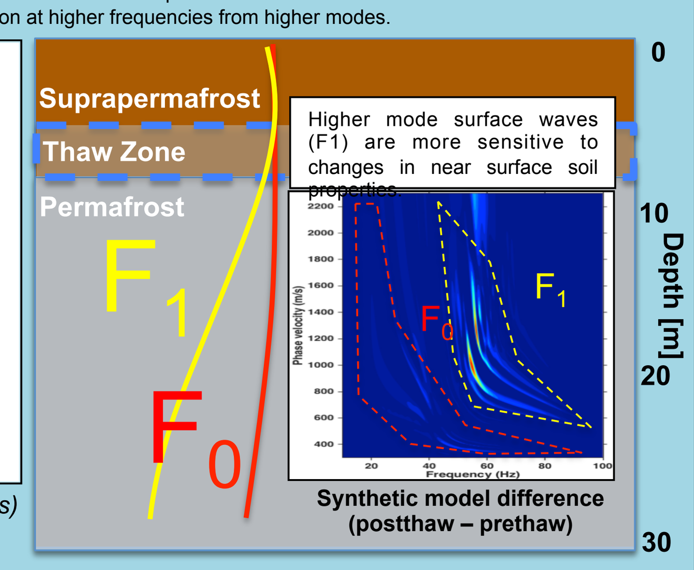
Given that large volumes of permafrost may be poised to thaw, what fraction of fluid is unfrozen at the suprapermafrost-permafrost interface? How does permeability evolve at the suprapermafrost-permafrost interface? How does cryotexture guide thaw mechanics and the coupled hydrology?

Rock Physics Interpretation of Seismic Results

Seismic velocities (Vp and Vs) decrease rapidly during thaw. However, the presence of a "seismic thaw precursor" may depend as much on freezing point depression due to solute concentration and pore size distribution. Differences in surface wave mode sensitivity kernels predict a disproportionate excitation at higher frequencies from higher modes.



Li, 2009 (UAF thesis)



Synthetic model difference (postthaw – prethaw)

Next Steps

- **Temperature:** Capture soil moisture heterogeneity using DTS records of diurnal cycle.
- **Surface Deformation:** Explore analytical solutions of soil drainage to model DSS observations.
- **Ambient Noise Seismology:** Extract and investigate other seismic phase arrivals, such as Love Waves and body waves; consider longer paths to enhance surface wave dispersion; Rayleigh wave ellipticity recorded by geophone/DAS may provide additional constraint on thaw evolution.
- **Calibrate existing THM modeling software using these observations.**

Summary

- **"Fast-forward":** A fieldscale permafrost warming experiment replicated top-down thaw (+25 °C at the permafrost table). While the unfrozen suprapermafrost zone expanded by an amount equivalent to a few decades, a multifaceted geophysical dataset was recorded that is being used to study the natural process of thermokarst development, calibrate physical models of interdependent thermal-hydro-mechanical processes, and identify potential thaw precursors for hazard mitigation.
- **Distributed Fiber Optic Geophysics:** Novel fiber optic sensing technology provided dense (0.25-1 sensor/meter), long-range (5 km), repeatable measurements of time-lapse subsurface temperature, subsidence/strain, and seismic properties. Using ambient surface waves generated by moving vehicles on a local road, Rayleigh wave speed over the thaw experiment was observed to change by <12% in correlation with precipitation/infiltration and drying cycles recorded by soil moisture content probes. An active source suggests body waves may be better suited to probing this interface, with the observed refracted SV traveltime changing >15% and attenuation changes consistent with increased moisture.

Acknowledgements

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