



NSF

**ARCTIC  
Data  
Center**

Scalable and Computationally  
Reproducible Approaches to  
Arctic

September 22, 2022

# Billions of Ice Wedge Polygons

*Transforming of BIG imagery into  
Arctic Science ready products*



**Chandi Witharana**  
Assistant Professor

**Mahendra Udawalpola**  
Postdoctoral Fellow



**Amit Hasan**  
Graduate student



**Elias Manos**  
Graduate student



Advanced Remote sensing Imaging and Analytics Lab (ARIAL)  
Department of Natural Resources and the Environment | University of Connecticut





# Permafrost Discovery Gateway (PDG)



*Navigating the new Arctic tundra through big data,  
artificial intelligence, and cyberinfrastructure*

[Award #s:1927872, 1927723, 1927729, 1927720 & 1927920]



**Kenton McHenry & Aiman Soliman**  
University of Illinois Urbana-Champaign



**Anna Liljedahl**  
Woodwell Climate Research Center  
[aliljedahl@woodwellclimate.org](mailto:aliljedahl@woodwellclimate.org)



**Matt Jones & Amber Budden**  
Arctic Data Center



**Ben Jones & Jennifer Moss**  
University of Alaska Fairbanks



**Chandi Witharana**  
University of Connecticut



**Jason Cervenec & Aaron Wilson**  
Ohio State University



**Gala Wind**  
NASA



**Michael Brubaker**  
Alaska Pacific University

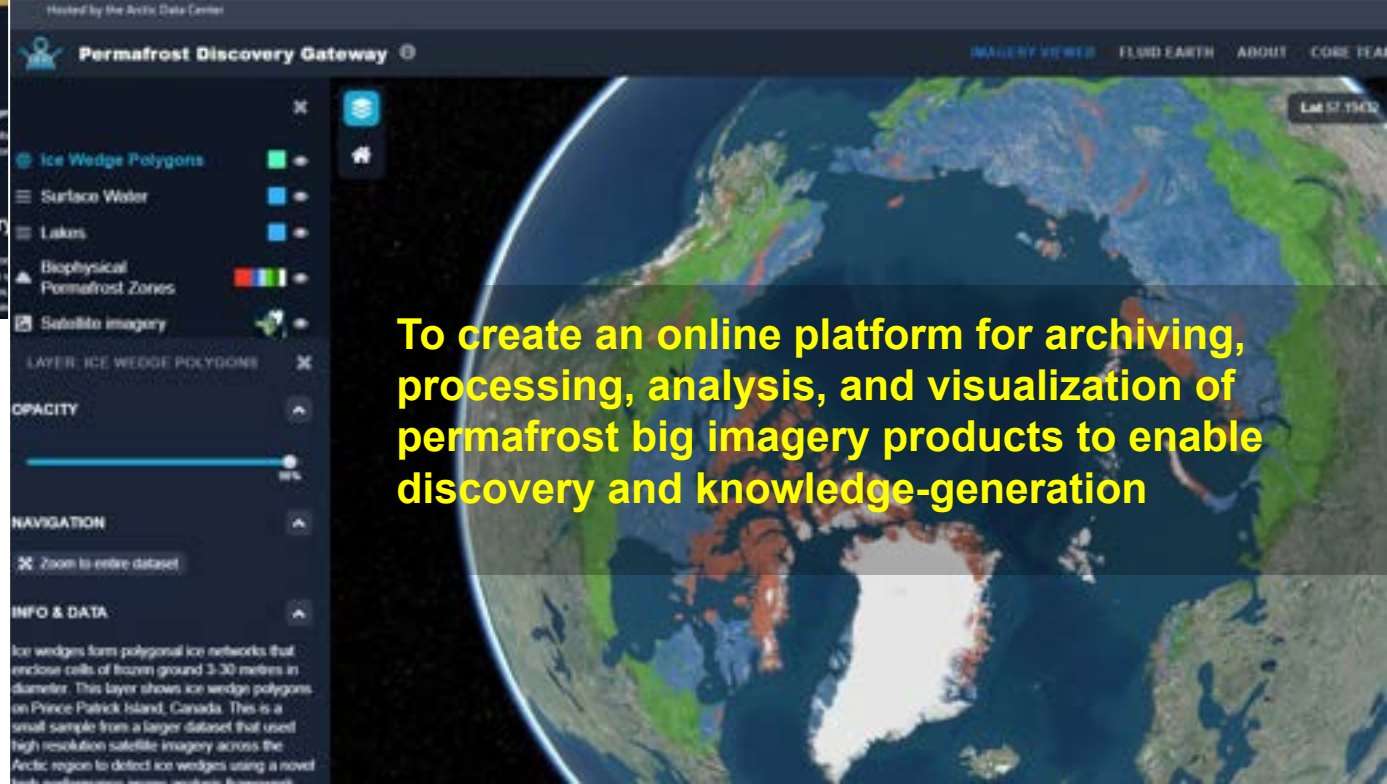


**Guido Grosse & Ingmar Nitze**  
Alfred Wegener Institute





# Permafrost Discovery Gateway

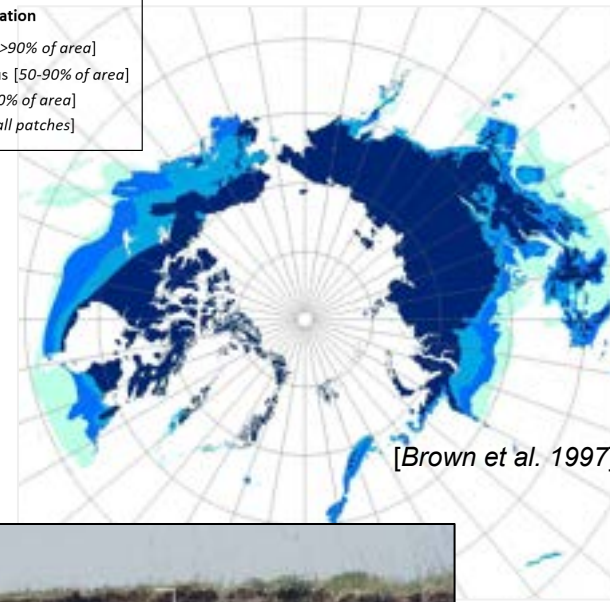
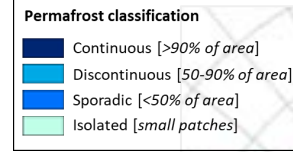


To create an online platform for archiving, processing, analysis, and visualization of permafrost big imagery products to enable discovery and knowledge-generation

<https://arcticdata.io/catalog/portals/permafrost>

# Arctic Permafrost

- **Sub-surface earth materials that stay below 0°C for at least 2 years in a row**
- 23 million km<sup>2</sup> of northern hemisphere land mass
- A critical component of the coupled atmosphere-ocean-land system
- ~**14%** Earth's carbon tied to permafrost
- Controls many ecological process as ground ice supports the surface and affects topography.
- Permafrost affects the outcome of climate-induced changes

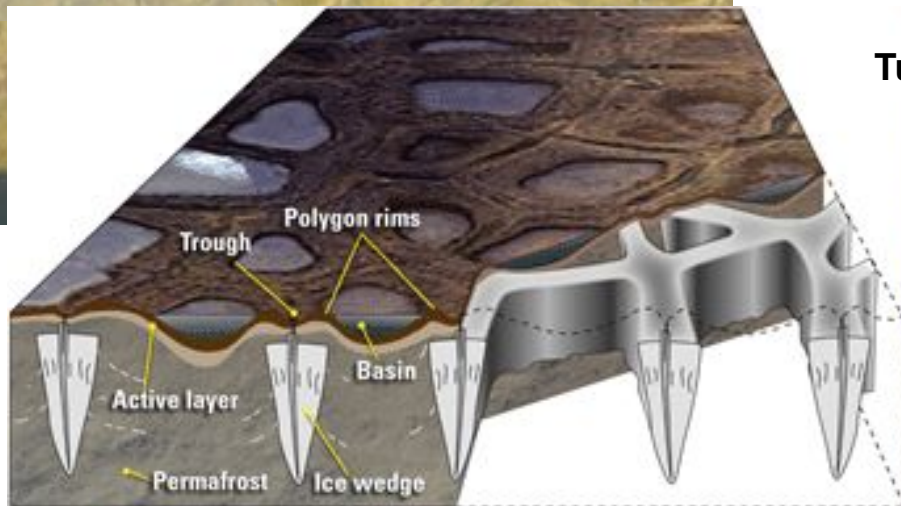


[Jorgensen and Grosse 2016, Schuur et al. 2015, Grosse et al. 2011]

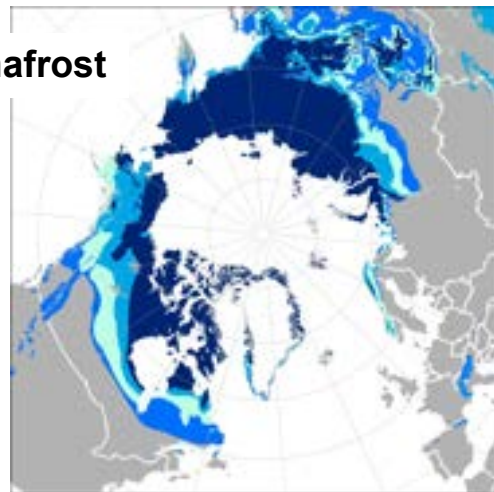
## Patterned ground

A network of small polygonal ponds and patches of wet/dry tundra

*-Archetypal polygonal pattern-*



## Permafrost

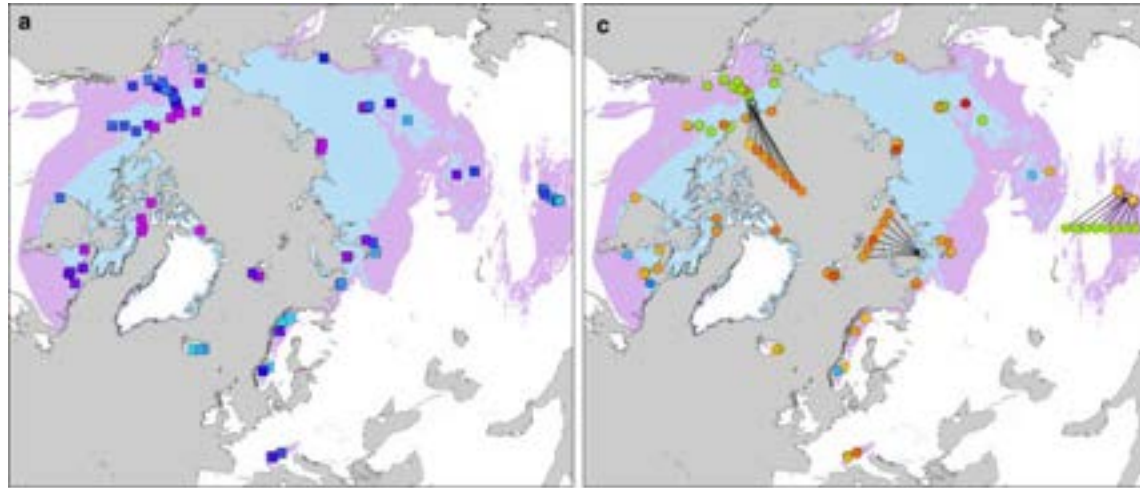


## Tundra



# Permafrost is Warming at a Global Scale

- Continuous permafrost zone -  $0.4^{\circ}\text{C}$  warming per decade
- Discontinuous permafrost zone -  $0.2^{\circ}\text{C}$  warming per decade



a-b Modern permafrost temperature (mean °C of 2014–2016)



c-d Temperature change rate of permafrost (°C per decade)

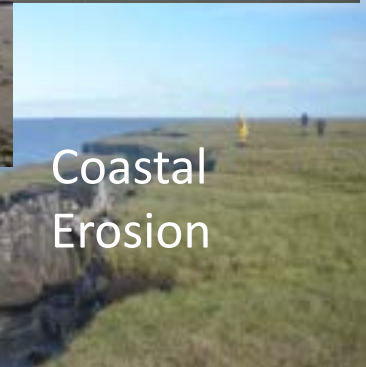


Continuous permafrost    Discontinuous permafrost

[Biskaborn et al., 2019]

# Response of permafrost tundra to climate change

- Re-organizes hydrological flow paths, soil processes, biogeochemical cycling, vegetation dynamics
- Compositional shift/biomass changes of vegetation due to altered nutrient availability and competitive interaction among species
- Shoreline erosion and differential ground subsidence
- Flipping carbon sink to carbon contributor



[Myers-Smith et al. 2011, Jones et al. 2011, Walvoord et al. 2012, Jorgenson et al. 2013, Potter et al. 2013; Lousada et al. 2018 ]

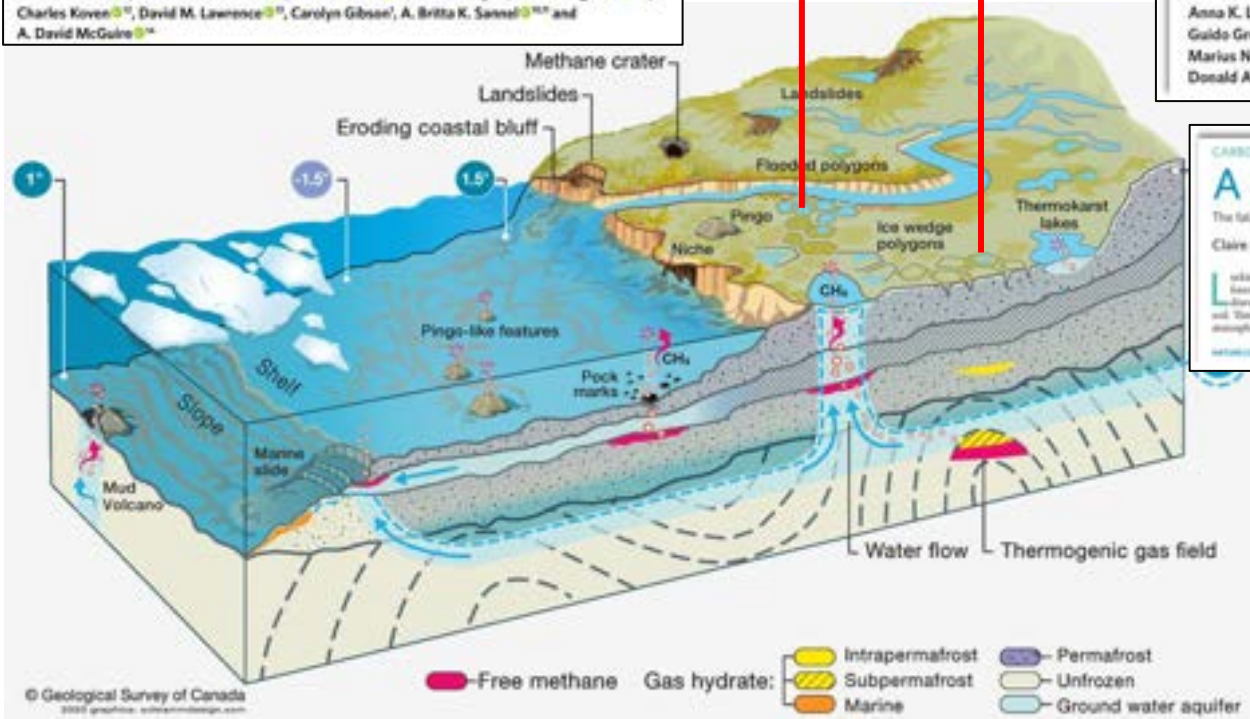
# Wake up calls.....

## Carbon release through abrupt permafrost thaw

Merritt R. Turetsky<sup>1,2\*</sup>, Benjamin W. Abbott<sup>3,4</sup>, Miriam C. Jones<sup>5,6</sup>, Katy Walter Anthony<sup>7,8</sup>, David Olefeldt<sup>9,10</sup>, Edward A. G. Schuur<sup>11</sup>, Guido Grosse<sup>12,13</sup>, Peter Kuhry<sup>14,15</sup>, Gustaf Hugelius<sup>16,17</sup>, Charles Koven<sup>18</sup>, David M. Lawrence<sup>19</sup>, Carolyn Gibson<sup>20</sup>, A. Britta K. Sannel<sup>21,22</sup> and A. David McGuire<sup>23</sup>

## Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology

Anna K. Liljedahl<sup>1\*</sup>, Julia Boike<sup>1</sup>, Ronald P. Daanen<sup>1</sup>, Alexander N. Fedorov<sup>2</sup>, Gerald V. Frost<sup>1</sup>, Guido Grosse<sup>1</sup>, Larry D. Hinzman<sup>2</sup>, Yoshihiro Iijima<sup>2</sup>, Janet C. Jorgenson<sup>3</sup>, Nadya Matveyeva<sup>10</sup>, Marius Necsoiu<sup>1</sup>, Martha K. Raynolds<sup>12</sup>, Vladimir E. Romanovsky<sup>13,14</sup>, Jörg Schulla<sup>15</sup>, Ken D. Tape<sup>1</sup>, Donald A. Walker<sup>10</sup>, Cathy J. Wilson<sup>16</sup>, Hironori Yabuki<sup>17</sup> and Donatella Zona<sup>18,19</sup>



CARBON STORAGE

## A permafrost carbon bomb?

The fate of permafrost soil carbon following thaw depends on hydrology

Claire C. Treat and Steve Frolking

Looking beneath Arctic tundra and boreal forest, there is a potential climate-altering carbon (C) store in the frozen soil. There is more than twice the amount of atmospheric C in northern permafrost soils, which are predicted to warm substantially by 2100. In these regions, the mean annual air temperature is generally below freezing, which has resulted in permafrost formation — where the ground is continuously frozen throughout the year, except for a thin (typically <1 m) seasonally-thawing surface soil. The carbon forms incorporation of organic matter into the permafrost and limits decomposition of readily available organic

matter throughout the year, except for a thin (typically <1 m) seasonally-thawing surface soil. The carbon forms incorporation of organic matter into the permafrost and limits decomposition of readily available organic

[nature.com/science/doi/10.1038/ngeo1209](https://doi.org/10.1038/ngeo1209)

nature  
 International journal of science

Letter · Published: 28 May 2014

## The effect of permafrost thaw on old carbon release and net carbon exchange from tundra

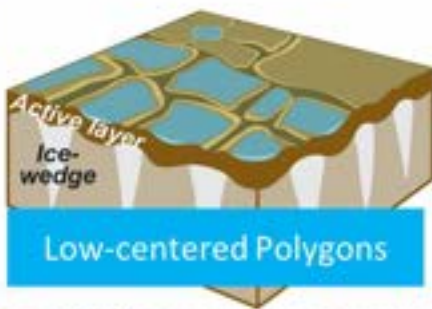
Edward A. G. Schuur<sup>1</sup>, Jason G. Vogel<sup>2</sup>, Katherine G. Crockett<sup>3</sup>, Barbara Lee<sup>4</sup>, James O. Sickman & T. E. Chalko<sup>5</sup>



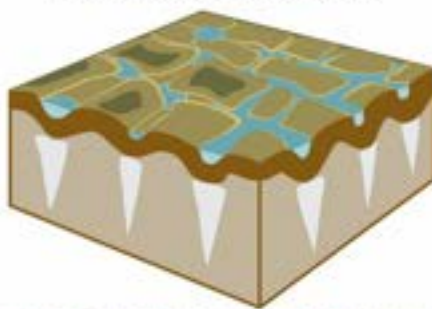
# Is topography stationary against climate change?

[Liljedahl et al., *Nature Geoscience* 2016]

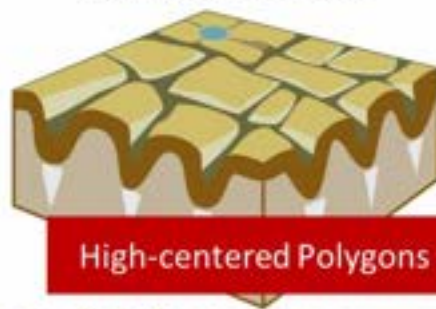
Undegraded



Initial degradation,  
*disconnected* troughs



Advanced degradation,  
*connected* troughs



Increased drainage

## Ground subsidence over degraded ice-wedges, resulting in high-centered polygons

Water is not draining away so the ground subsidence results in trough-ponds



Water is draining away as runoff. The cracks on the sides of the troughs indicate actively degrading ice-wedges below the trough



Prudhoe Bay, Alaska | July 2019 | Photo: *Anna Liljedahl*

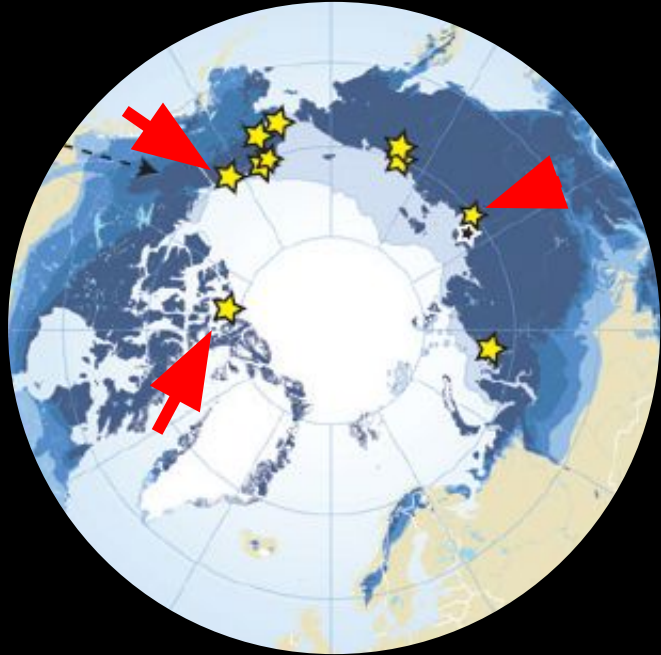


*The Arctic is changing rapidly through permafrost thaw*



*We are unable to keep up monitoring via traditional science approaches.*

What happens, When,  
Where ???...



Observed landscape-wide ice-wedge  
degradations

[Liljedahl et al., Nature Geoscience 2016]

**Ice-wedge polygon extent is largely  
unknown.**

*... what are the current extents of  
ice-wedge polygon landscape ?*

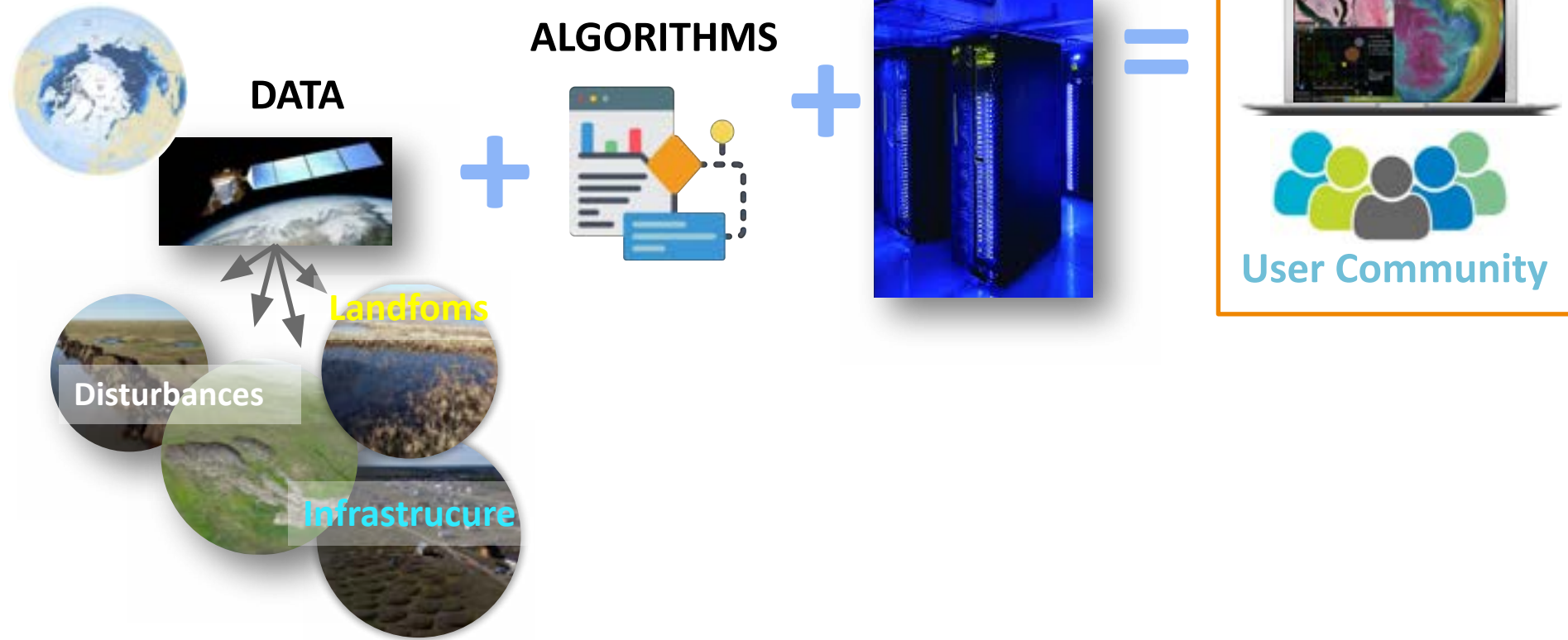
**Documentation of pan-Arctic  
permafrost degradation is patchy  
both spatially and temporally.**

*....what are successional stages of  
ice-wedge polygons across Arctic  
tundra ?*

**Commercial satellite [BIG] imagery  
to rescue.**

*....Can we produce an ice-wedge  
polygon map for the pan-Arctic  
polygonal tundra ?*

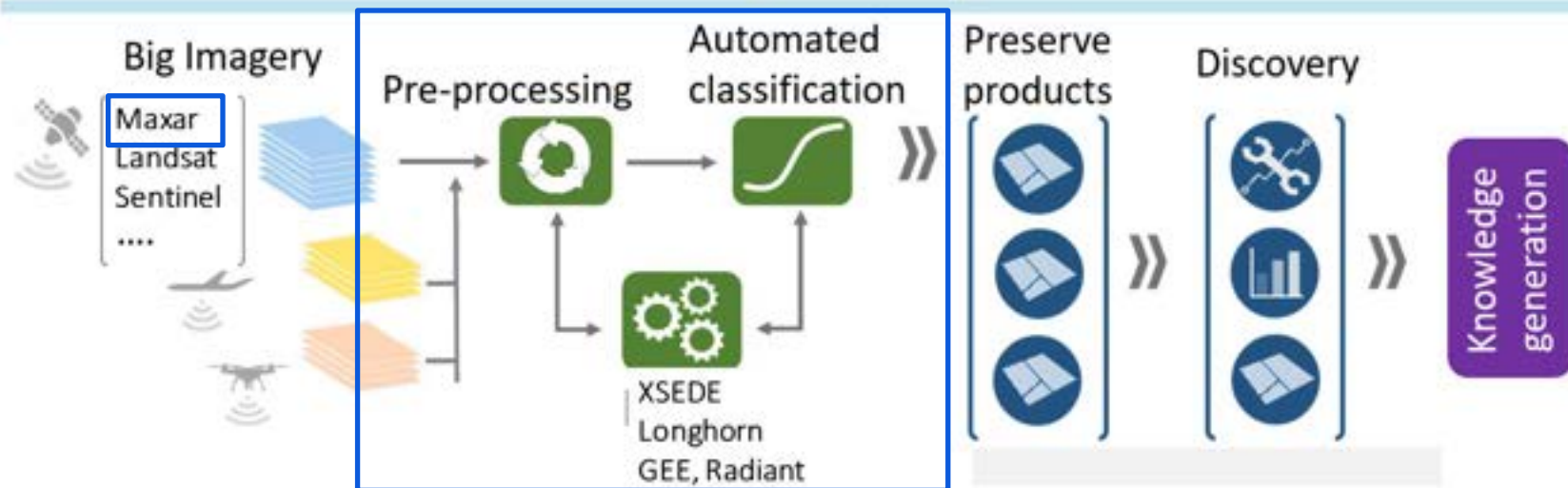
# Big Idea.....



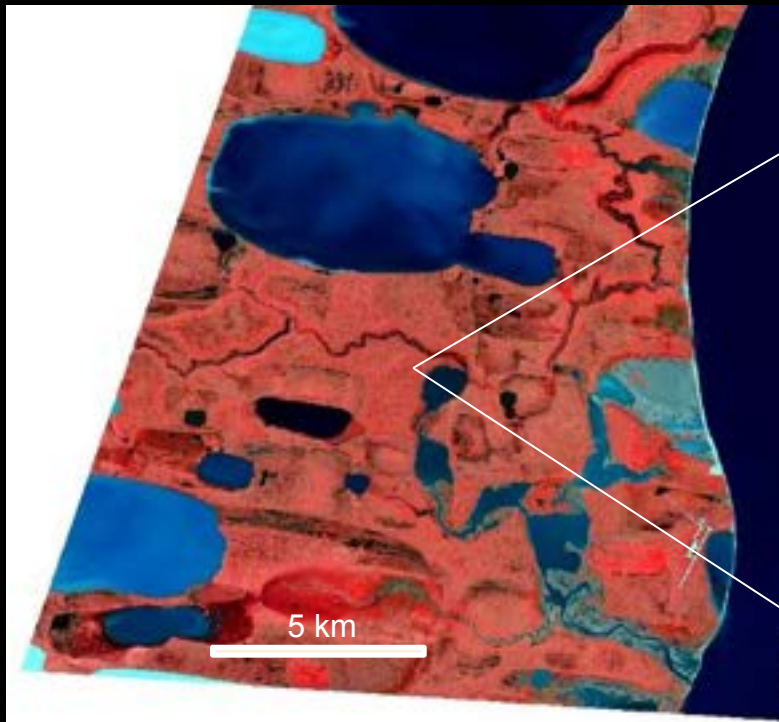
# PDG Framework

## 1. Data Creation

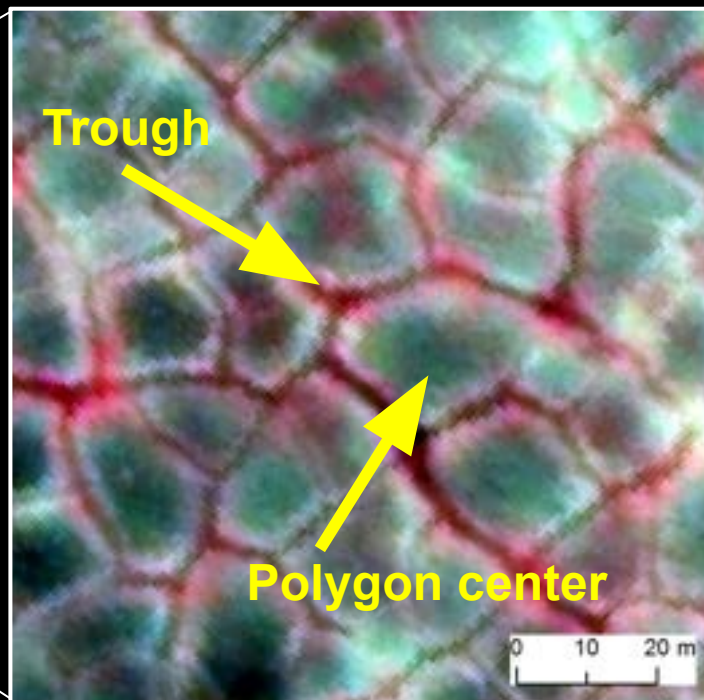
## 2. Data Visualization



WorldView-2 commercial satellite image [0.5m resolution, July 2016]

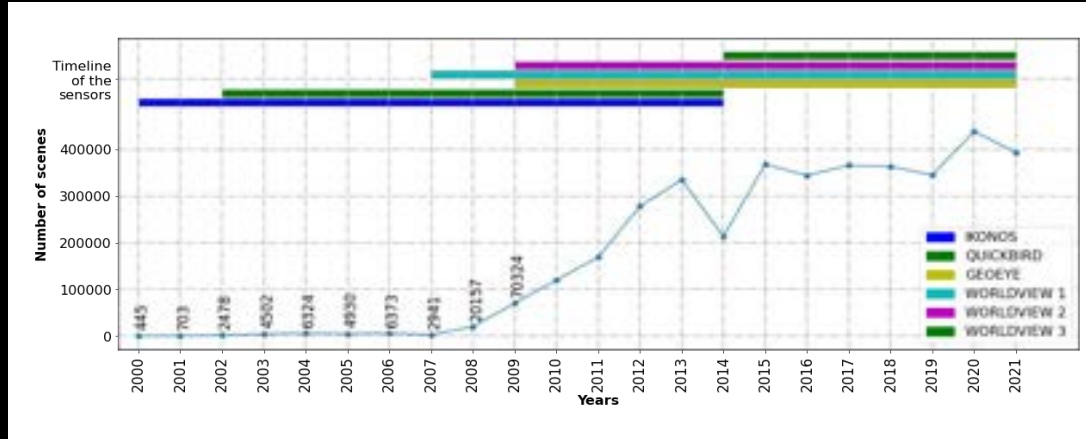


Ice-wedge Polygons seen in High-res Satellite Imagery



[Image copyright DigitalGlobe]

# Maxar Commercial Satellite Imagery Coverage (2000 – 2021)



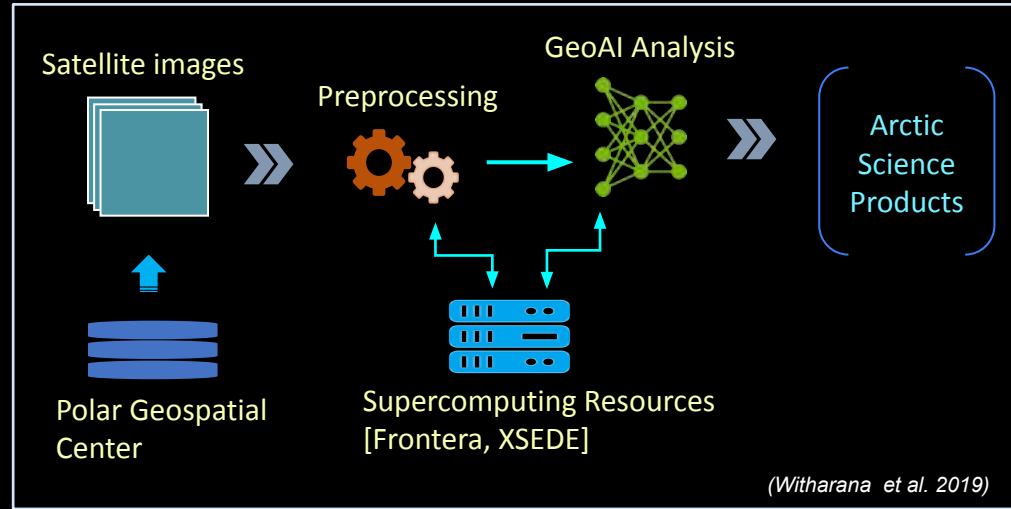
- 0.5 m resolution
- > 5 million image scenes
- > 2 PB data
- Pan-Arctic coverage (60° N)
- Can access via Polar Geospatial Center

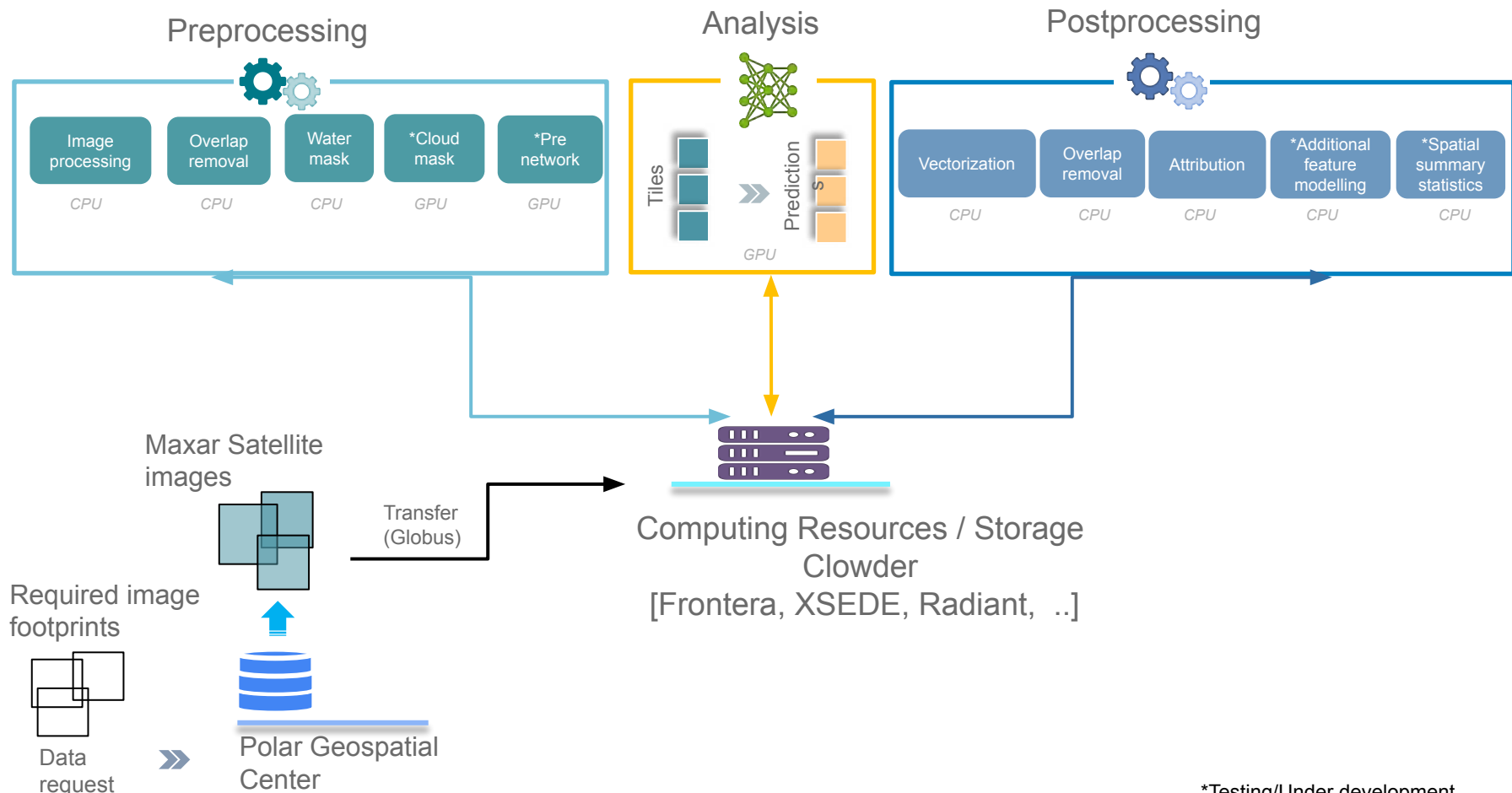
*(Plots and maps produced based on the satellite image footprints provided by the Polar Geospatial Center, University of Minnesota)*



# Mapping application for Arctic Permafrost Land Environment - **MAPLE**

- Operational-scale GeoAI pipeline
- Translation of **big** commercial imagery into science-ready products
- Production of first pan-Arctic ice-wedge polygon map
- Transferability across image data and targets of interest
- Scalability and interoperability across heterogenous computing resources



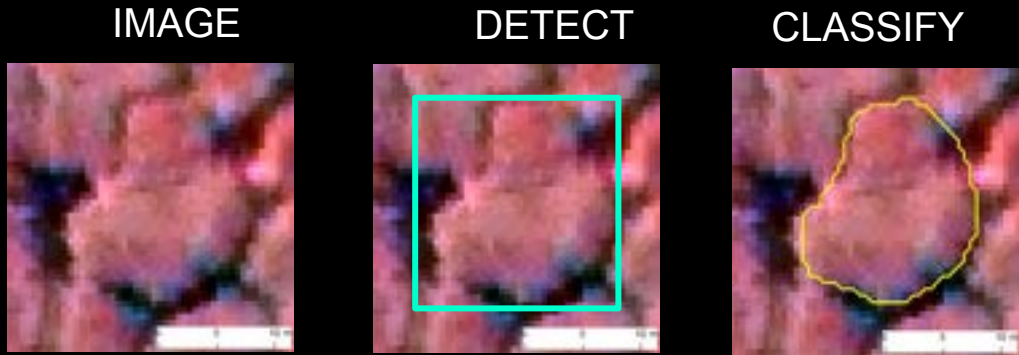


\*Testing/Under development

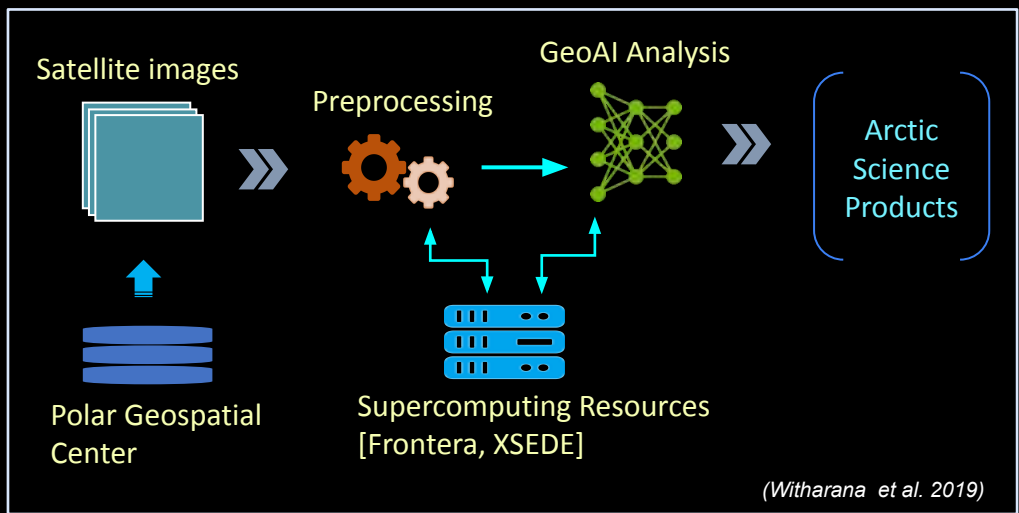
# Deep Learning Convolutional Neural Nets (CNNs)

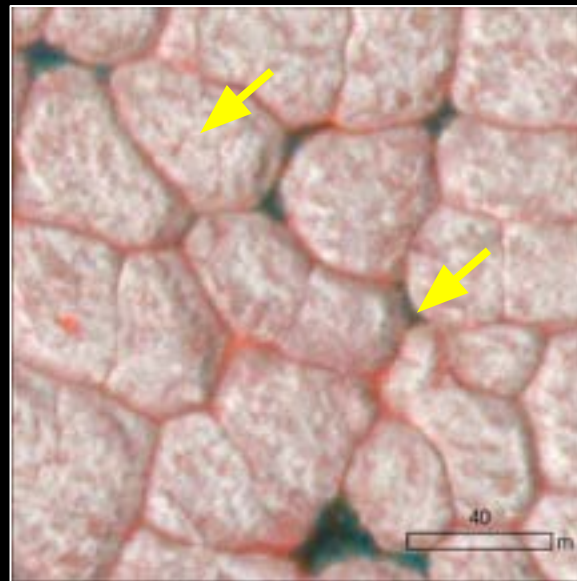
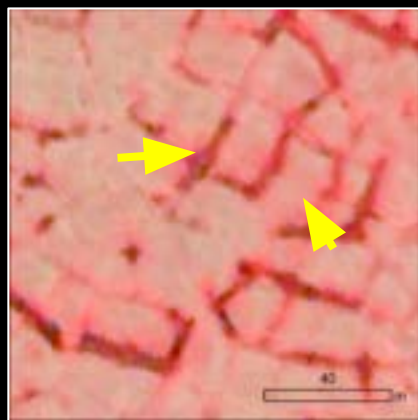
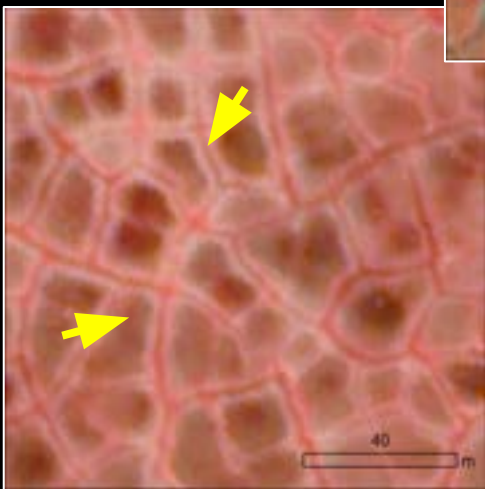
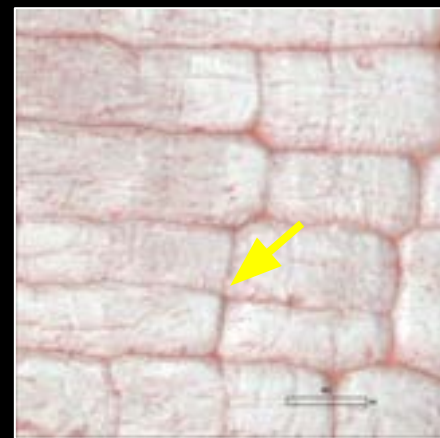
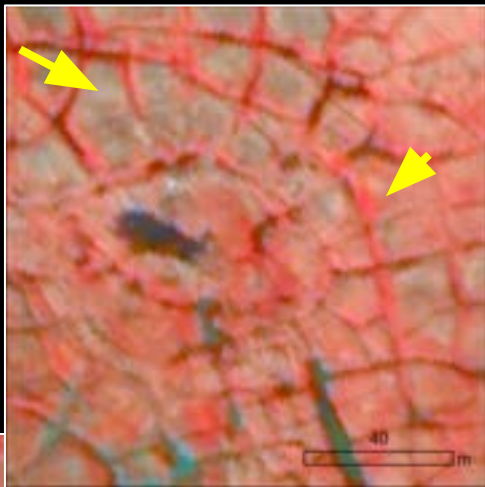
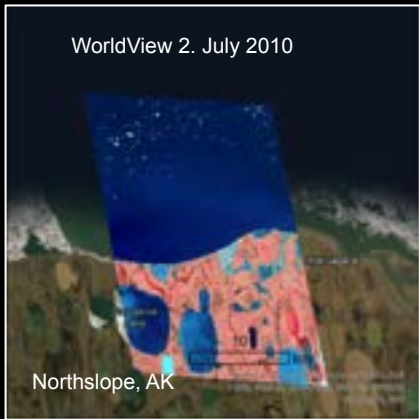
## *Semantic object instance segmentation*

Process of associating each pixel of an image with a class label, (such as *flower*, *person*, *road*, *sky*, *ocean*, etc.).



Example CNN architectures:  
Mask RCNN, U-Net

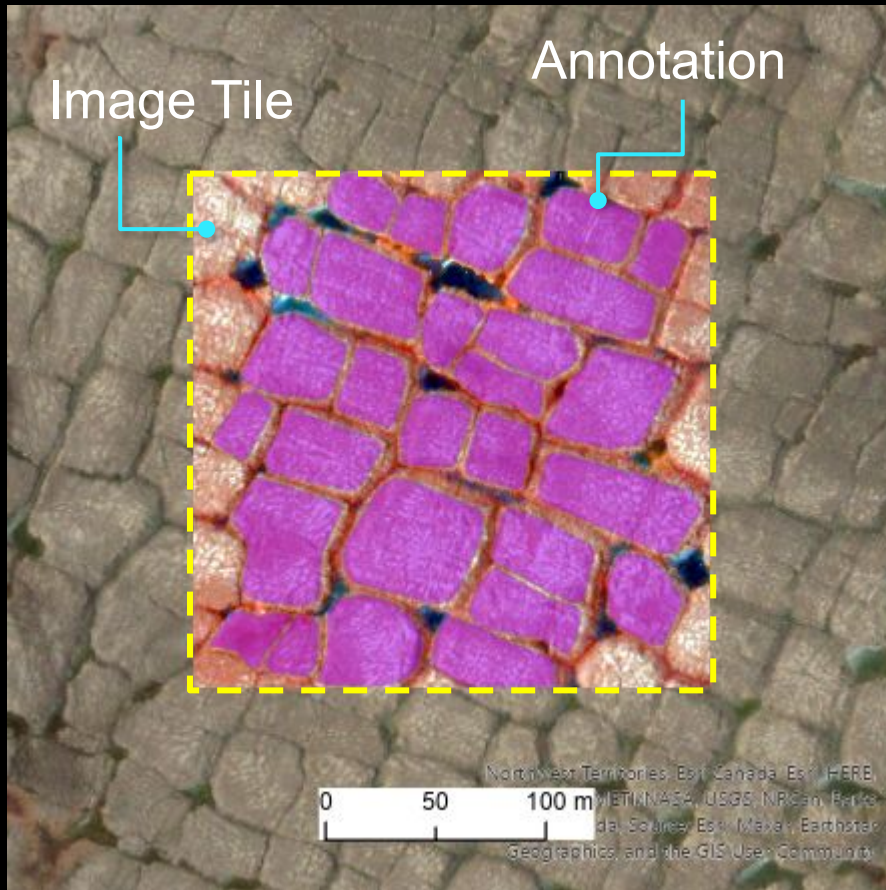




Imagery Copyright DigitalGlobe, Inc

Imagery © 2010, 2017 DigitalGlobe, Inc

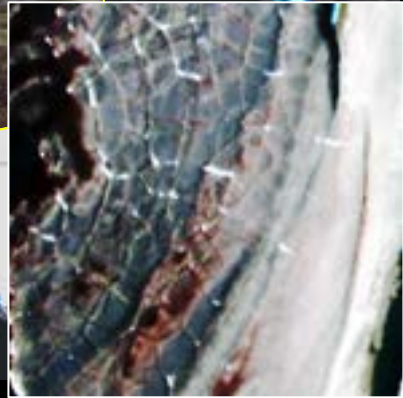
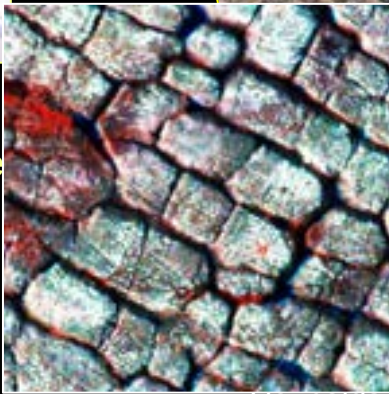
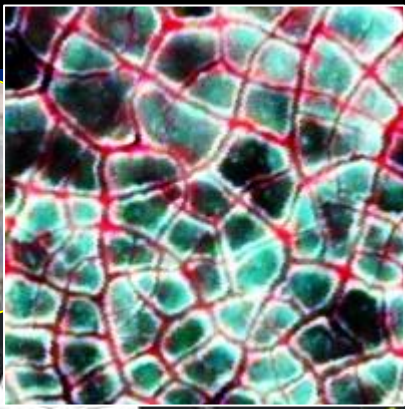
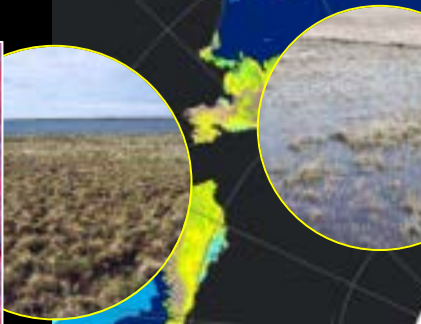
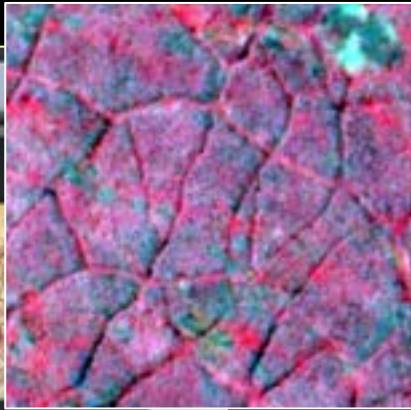
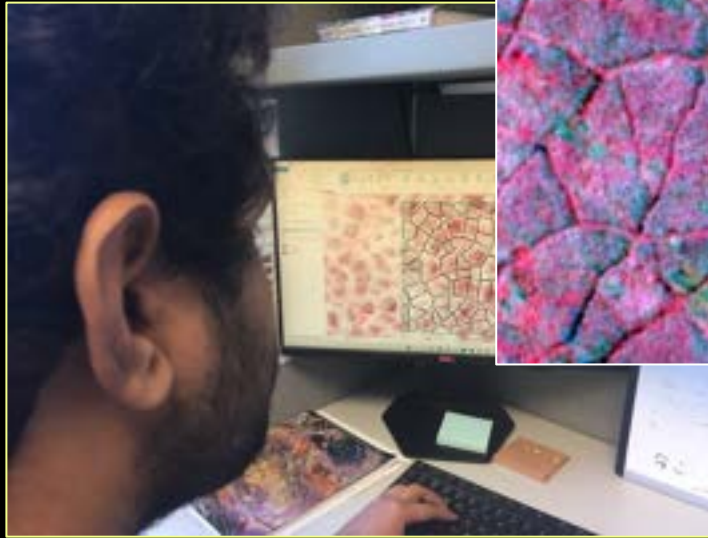
# Manual Annotation



Average # of targets per Tile: 55  
Average annotation time per tile: 20 minutes

Tiles	Individual targets
743	41,018

# Manual Annotation



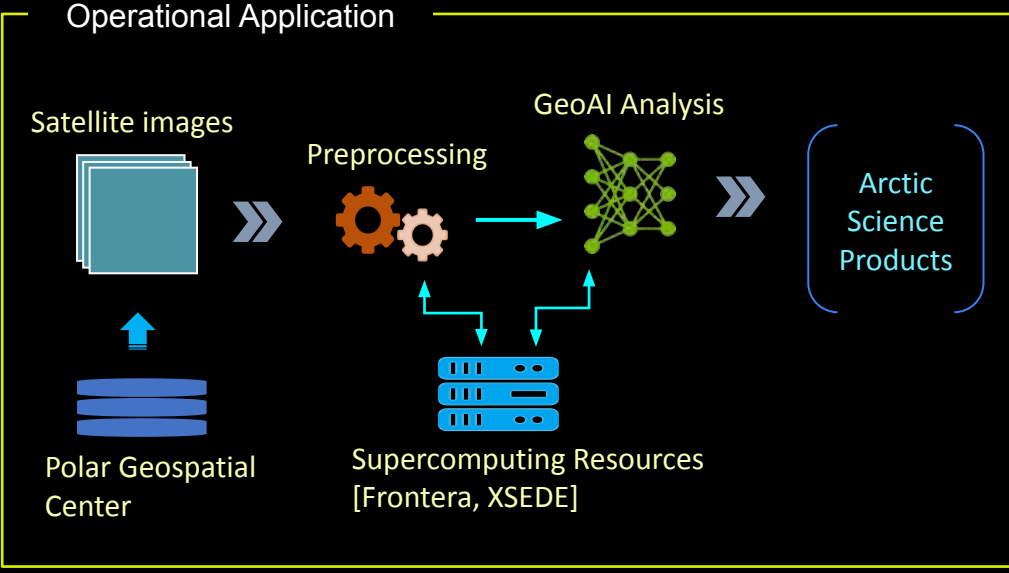
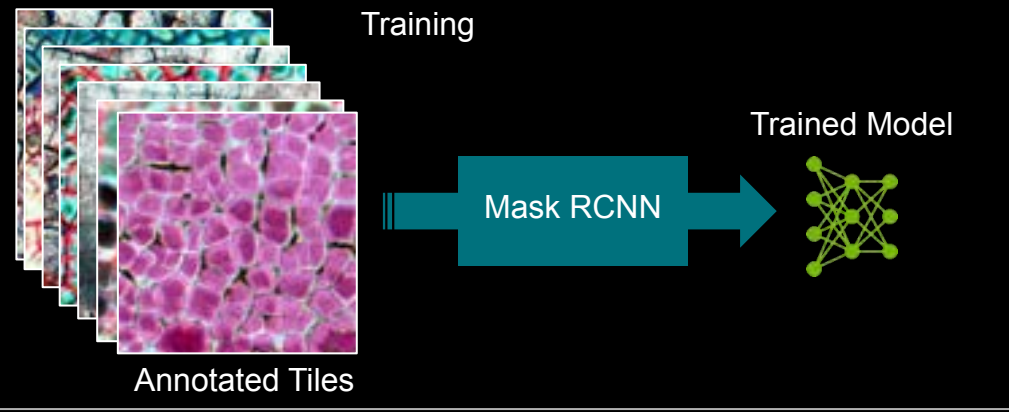
ck)  
rdrock)  
forb tundra  
oss tundra  
tundra  
ub tundra

■ Sedge, moss, dwarf-shrub wetland  
■ Sedge, moss, low-shrub wetland  
■ Fresh water

Average # of targets per Tile: 55  
Average annotation time per tile: 20 minutes

Tiles	Individual targets
743	41,018

Arctic vegetation map, Reynolds et al. 2019



**Testing**

[Photogrammetric Engineering & Remote Sensing, 2022](#)

### An Optimal GeoAI Workflow for Pan-Arctic Permafrost Feature Detection from High-Resolution Satellite Imagery

Mahendra H. Udawalpola, Amir Hasan, Anna Liljedahl, Alisan Soliman, Jeffrey Trevino, and Chand Witharana

**Abstract**  
 High-resolution satellite imagery enables transformational opportunities to observe, map, and document the macro-geographic transitions occurring in Arctic polygonal tundra at multiple spatial and temporal frequencies. Knowledge discovery through artificial intelligence, big imagery, and high-performance computing (HPC) resources is just starting to be realized in Arctic permafrost science. We have developed a novel high-performance image-analysis framework - Mapping Application for Arctic Permafrost Land Environment Analysis (MAPLE) - that enables the integration of operational-scale GeoAI capabilities into Arctic geospatial modeling. Heterogeneous Arctic heterogeneous HPC systems and optimal usage of computational resources are key design goals of MAPLE. We systematically compared the performance of four different MAPLE workflow designs on two HPC systems. Our experimental results on resource utilization, total time to completion, and overhead of the candidate designs suggest that the design of an optimal workflow largely depends on the HPC system architecture and underlying service-user accounting model.

workload is characterized by its scalability or running time. Typically, an HPC workload consists of a single job that coordinates multiple processes which run at the same time. When running these jobs, input/output requirements are important. Usually, HPC tasks operate on a small volume of data and HPC workloads operate on large volumes of data. But in running many HPC jobs, the limitations of input/output bandwidth become significant. Usually, most supercomputers are designed for HPC workloads. Harter et al. (2019) argue that new applications require a paradigm shift in computing architectures to address large data sets, deep-learning algorithms, and hybrid workloads using both HPC and HPC. It is important to find out how applications with hybrid workloads can be run efficiently in existing HPC environments. Remote sensing (RS) big-data applications typically consist of hybrid workloads requiring efficient use of existing HPC systems. Lee et al. (2011) reviewed advances in HPC applied to remote sensing problems, and in particular HPC-based platforms, such as multi-processor systems and large-scale and heterogeneous networks of computers.

A scientific application of HPC resources for translating big satellite imagery into science-ready products can enable knowledge discovery

Annotation

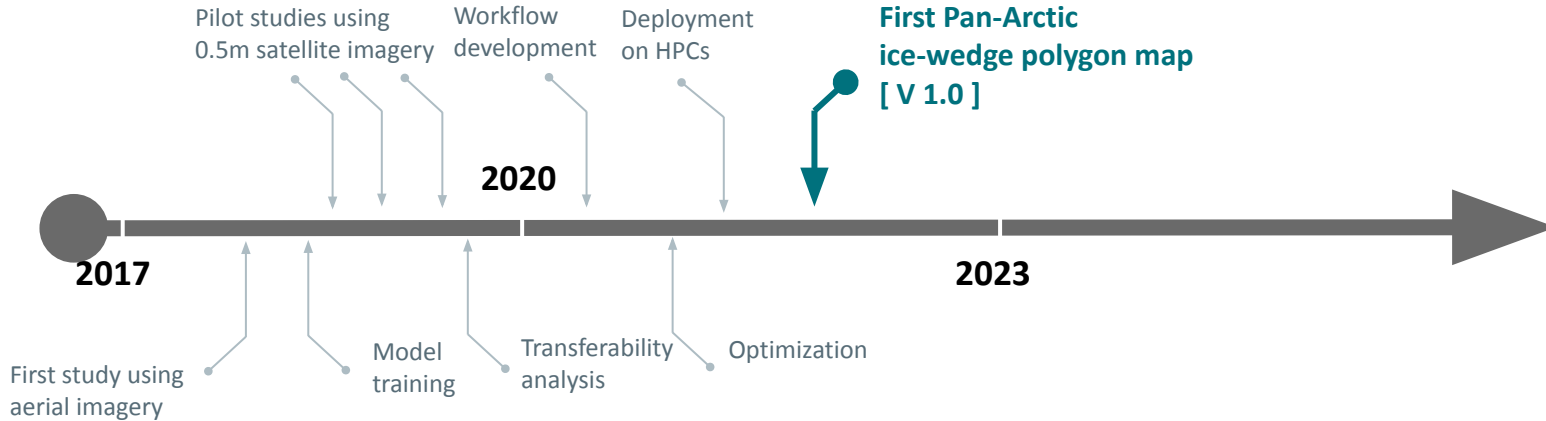
Detection

# Timeline of MAPLE



ARCSS

Patterns, Dynamics, and Vulnerability of Arctic Polygonal Ecosystems: From Ice-Wedge Polygon to Pan-Arctic Landscapes



NNA

The Permafrost Discovery Gateway: Navigating the new Arctic tundra through Big Data, artificial intelligence, and cyberinfrastructure





# Automated Recognition of Ice-wedge Polygons from Maxar Imagery

So far, we have mapped

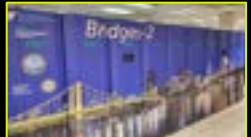
**> 1 billion**

individual ice-wedge polygons ...

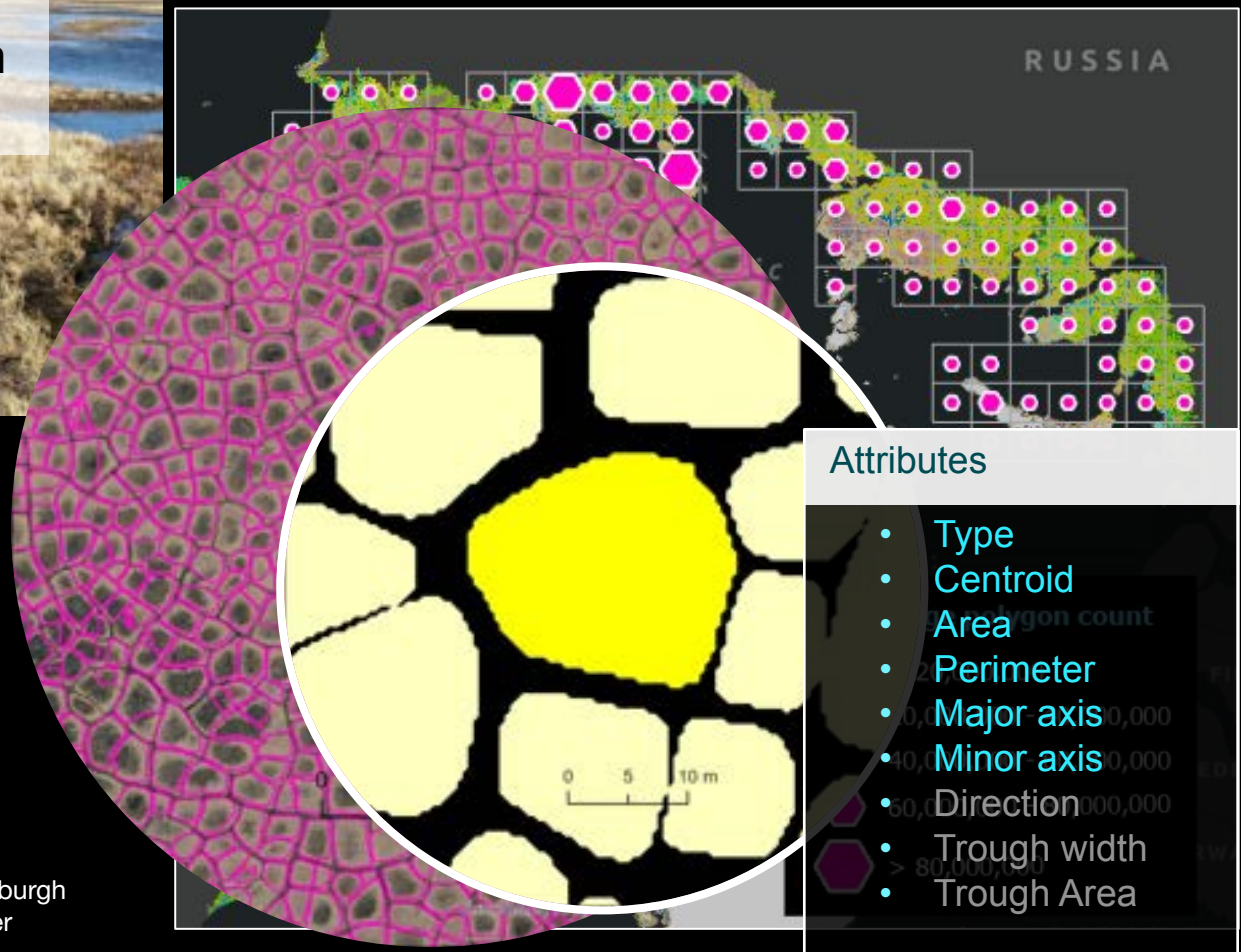
- Over 3 million km<sup>2</sup> of Tundra
- > 30,000 Maxar image scenes
- > 250 TB of image data



Frontera supercomputer at the Texas Advanced Computing Center (TACC)

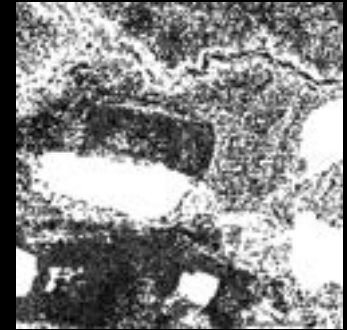
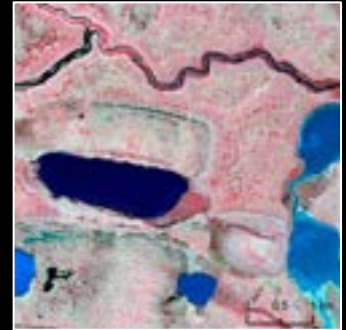
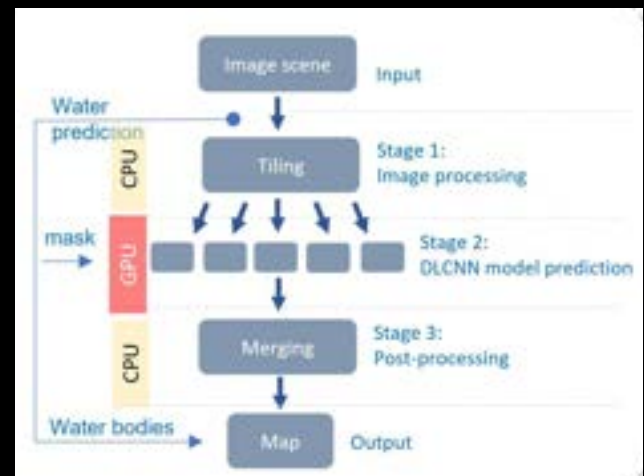
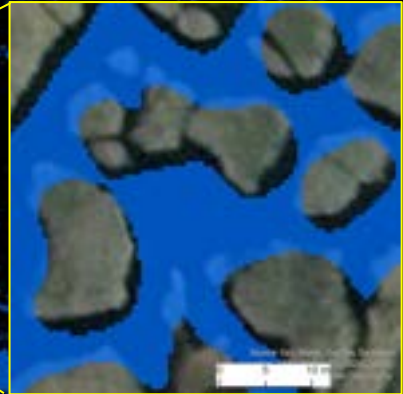
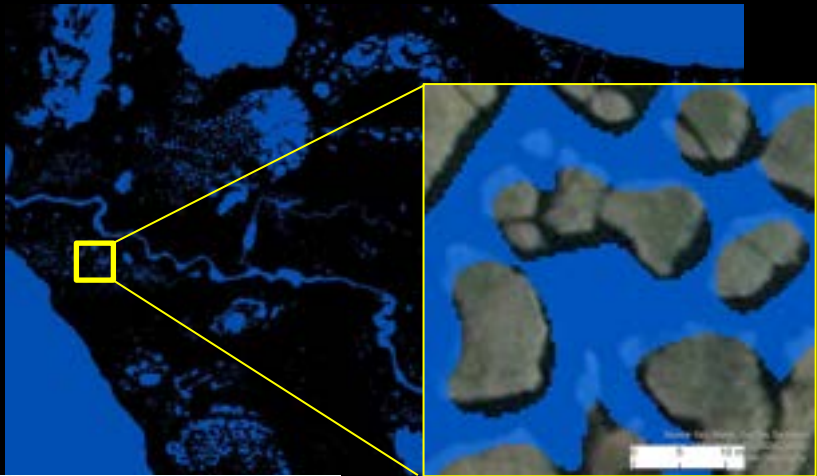


XSEDE Bridges-2 Pittsburgh Supercomputing Center



Attributes	
•	Type
•	Centroid
•	Area
•	Perimeter
•	Major axis
•	Minor axis
•	Direction
•	Trough width
•	Trough Area

# Surface water extraction from Maxar imagery

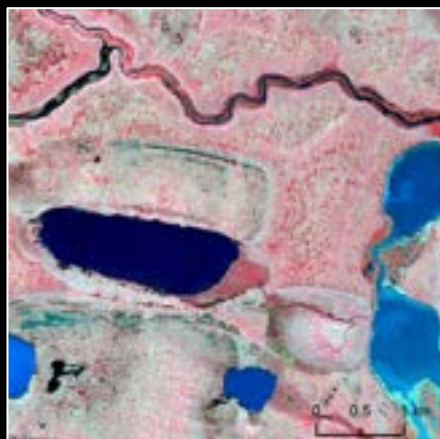
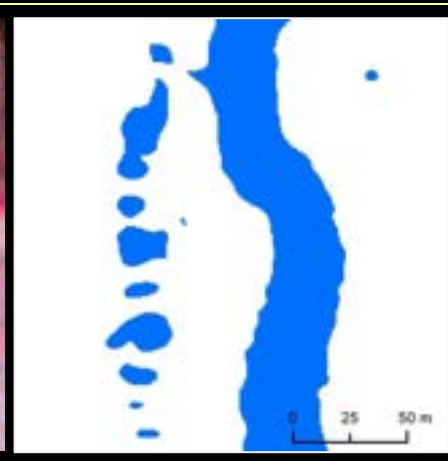
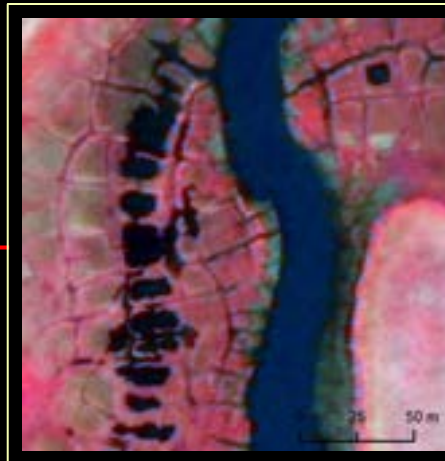
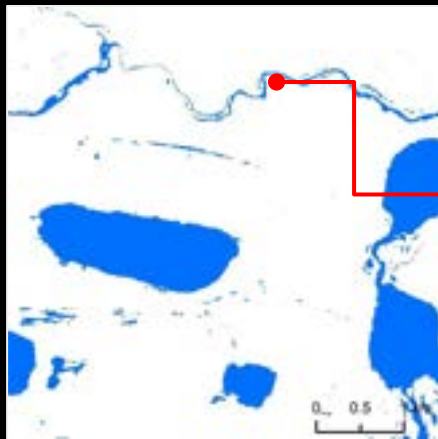


Ice-wedge polygons

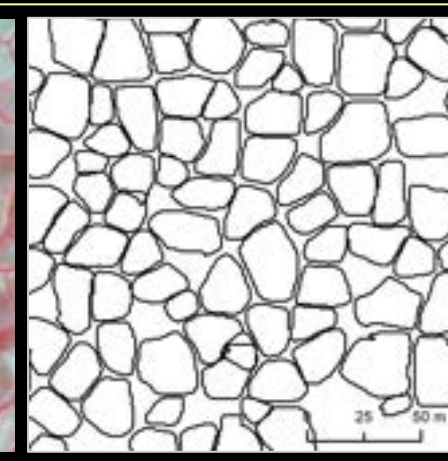
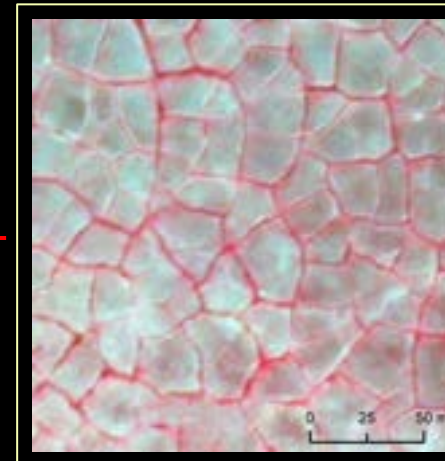
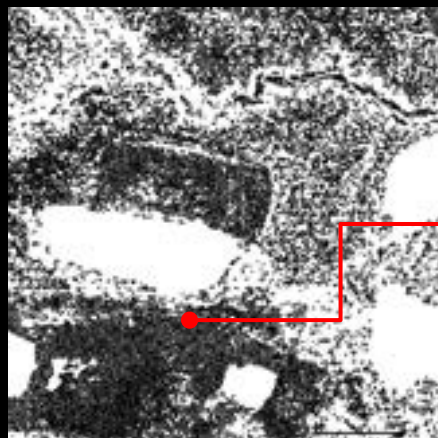
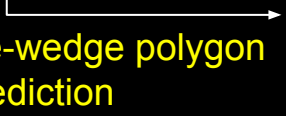
Water bodies

**Remote Sensing**  
Monitoring the Transformation of Arctic Landscapes: Automated Identification, Change Detection of Lakes Using Very High Resolution Imagery  
Kaiser et al. 2021

Surface water prediction



Ice-wedge polygon prediction

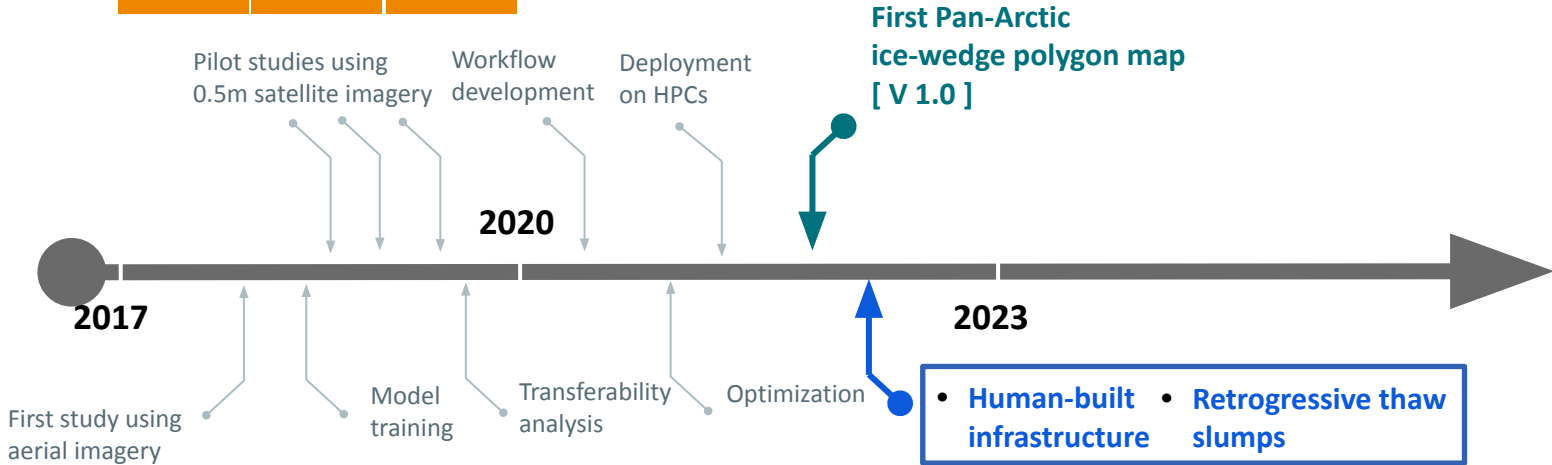


# Ongoing additions to MAPLE



ARCSS

Patterns, Dynamics, and Vulnerability of Arctic Polygonal Ecosystems: From Ice-Wedge Polygon to Pan-Arctic Landscapes

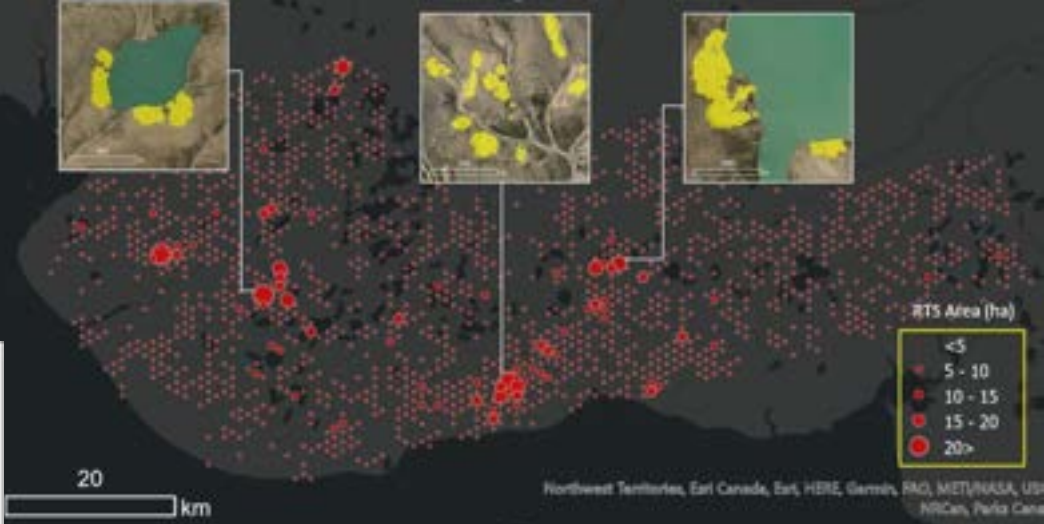
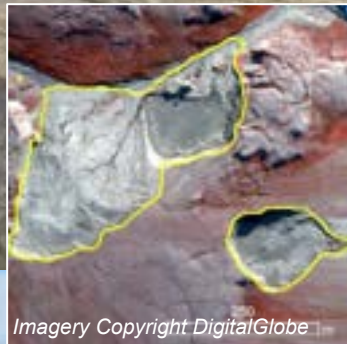


NNA

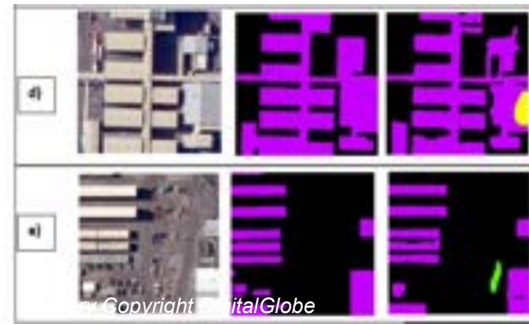
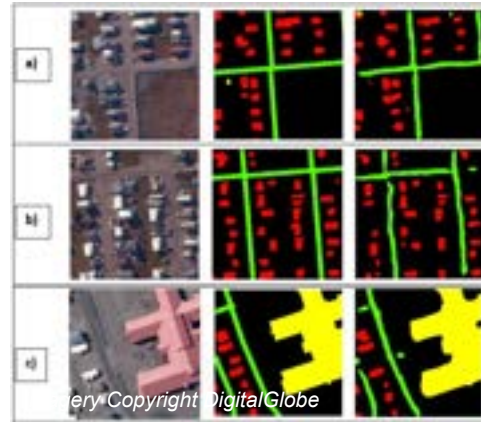
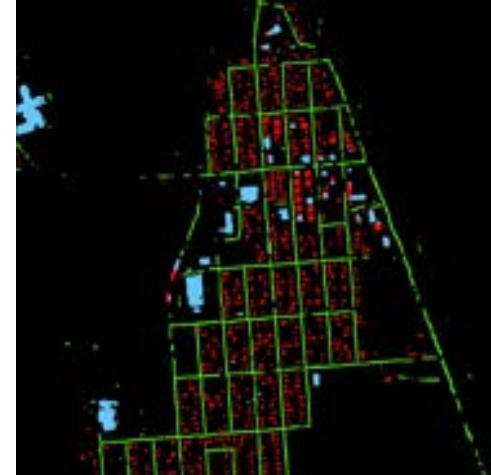
The Permafrost Discovery Gateway: Navigating the new Arctic tundra through Big Data, artificial intelligence, and cyberinfrastructure



# Automated Recognition of Retrogressive Thaw Slumps from Maxar Imagery



# Automated Recognition of Human-Built Infrastructure from Maxar Imagery



Selected model predictions on the testing dataset from Harrow and Prudhoe Bay sites. (a-d) each contain the input image tile, annotated image tile showing true output, and output predicted by model.

- Class**
- Background
  - Road
  - Residential/Commercial
  - Public
  - Industrial

Manos et al. (2022)





NSF

**ARCTIC  
Data  
Center**

Scalable and Computationally  
Reproducible Approaches to  
Arctic

September 22, 2022

# Billions of Ice Wedge Polygons

*Transforming of BIG imagery into  
Arctic Science ready products*



**Chandi Witharana**  
Assistant Professor

**Mahendra Udawalpola**  
Postdoctoral Fellow



**Amit Hasan**  
Graduate student



**Elias Manos**  
Graduate student



Advanced Remote sensing Imaging and Analytics Lab (ARIAL)  
Department of Natural Resources and the Environment | University of Connecticut

