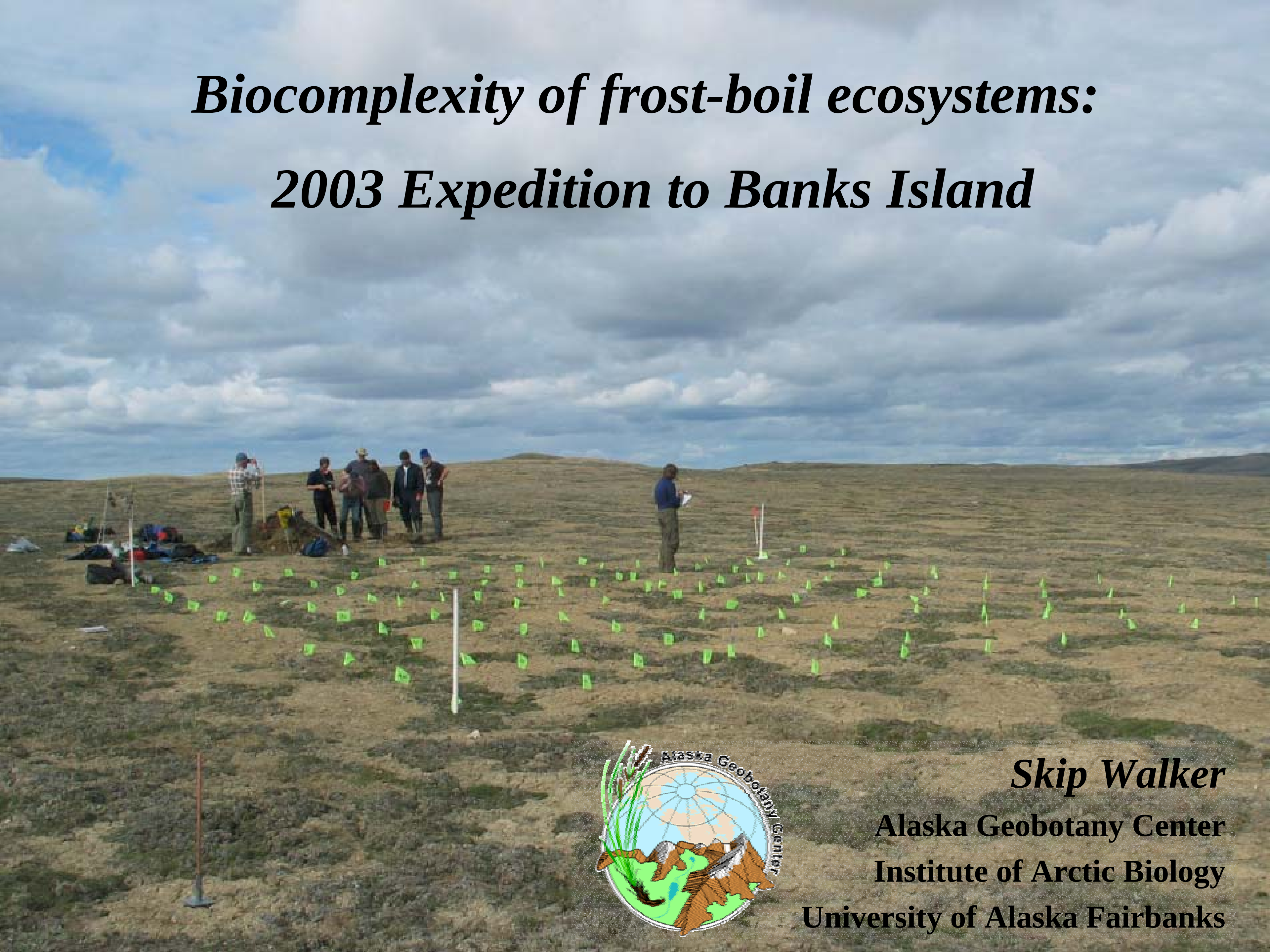


Biocomplexity of frost-boil ecosystems: 2003 Expedition to Banks Island

Skip Walker

Alaska Geobotany Center

Institute of Arctic Biology

University of Alaska Fairbanks

NSF Biocomplexity in the Environment (BE) Initiative

• *Stresses the richness of biological systems and their* ***capacity for adaptation*** *and* ***self-organizing behavior****.*

• *Emphasizes research with:*

(a) a high degree of ***interdisciplinarity****;*

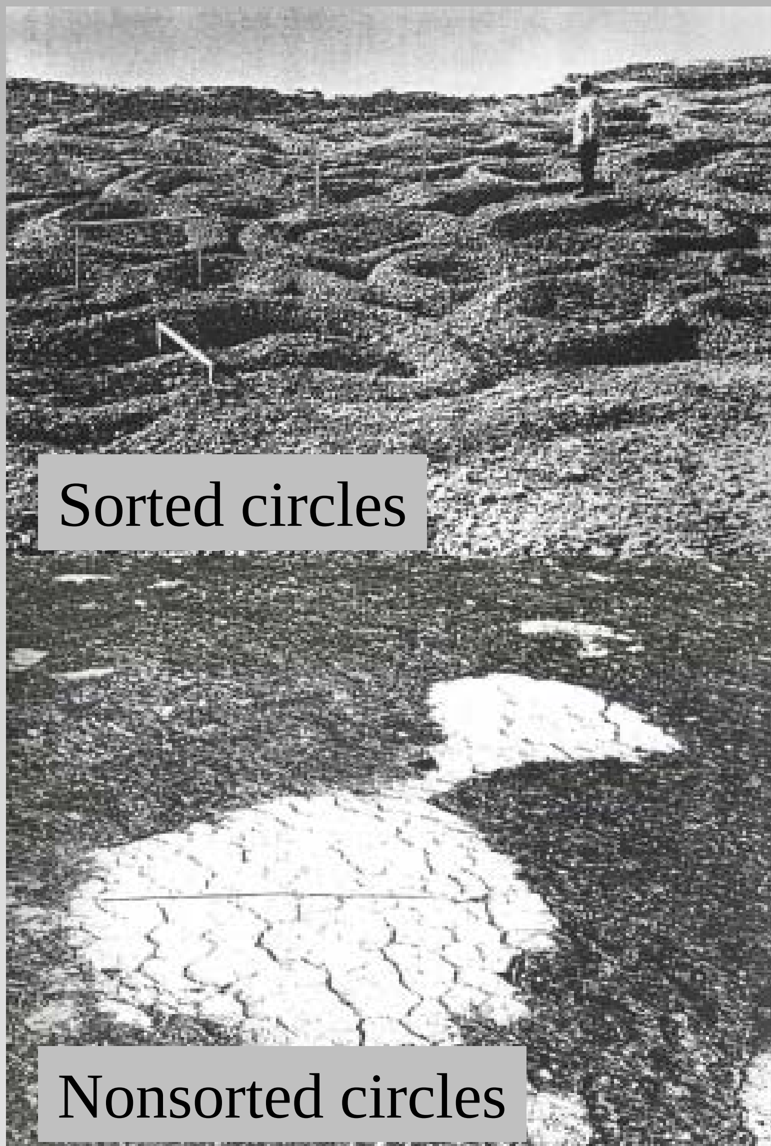
(b) a focus on ***complex environmental systems that include interactions of non-human biota or humans****; and*

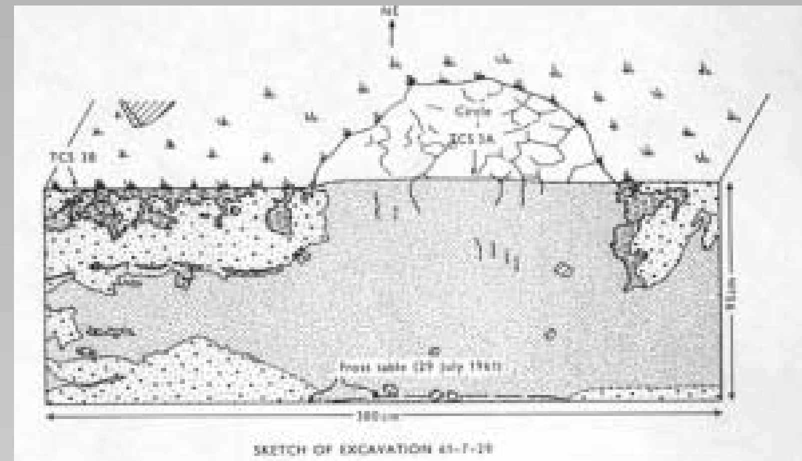
(c) a focus on systems with high potential for exhibiting ***non-linear behavior****.*

•*Emphasizes,* ***quantitative modeling****, simulation, analysis, and visualization methods are emphasized,* ***integration of research and education,*** *and a* ***global perspective****.*

•*Five topical areas: 1. Dynamics of Coupled Natural and Human Systems (CNH);* ***2. Coupled Biogeochemical Cycles (CBC);*** *3. Genome-Enabled Environmental Science and Engineering (GEN-EN); 4. Instrumentation Development for Environmental Activities (IDEA); 5. Materials Use: Science, Engineering, & Society (MUSES).*

What are frost boils?





Frost boil: “a patterned ground form that is equidimensional in several directions with a dominantly circular outline which lacks a border of stones…”

van Everdingen 1998

- Frost “boil” is a misnomer because no “boiling” is involved.
- Closest term in Russian is Piyatnoe medalion - “frost medallion”
- Moroznoe kepenie - frost churning due to needle-ice formation.
- Also “frost scar”, “mud circle”, “mud boil”, “nonsorted circles”
- Pyatneestaya tundra: “spotted tundra” in Russian

Figures from Washburn 1980

“Spotted” tundra

- ***Best developed where the mean July temperature is 5-9˚ C.***
- ***In silty soils.***
- ***1-3 m diameter circles.***
- ***20-30 frost boils/ 10 m²***

Subzone D, Kuparuk oil field, Arctic Coastal Plain, Alaska

Subzone D, Prudhoe Bay, AK

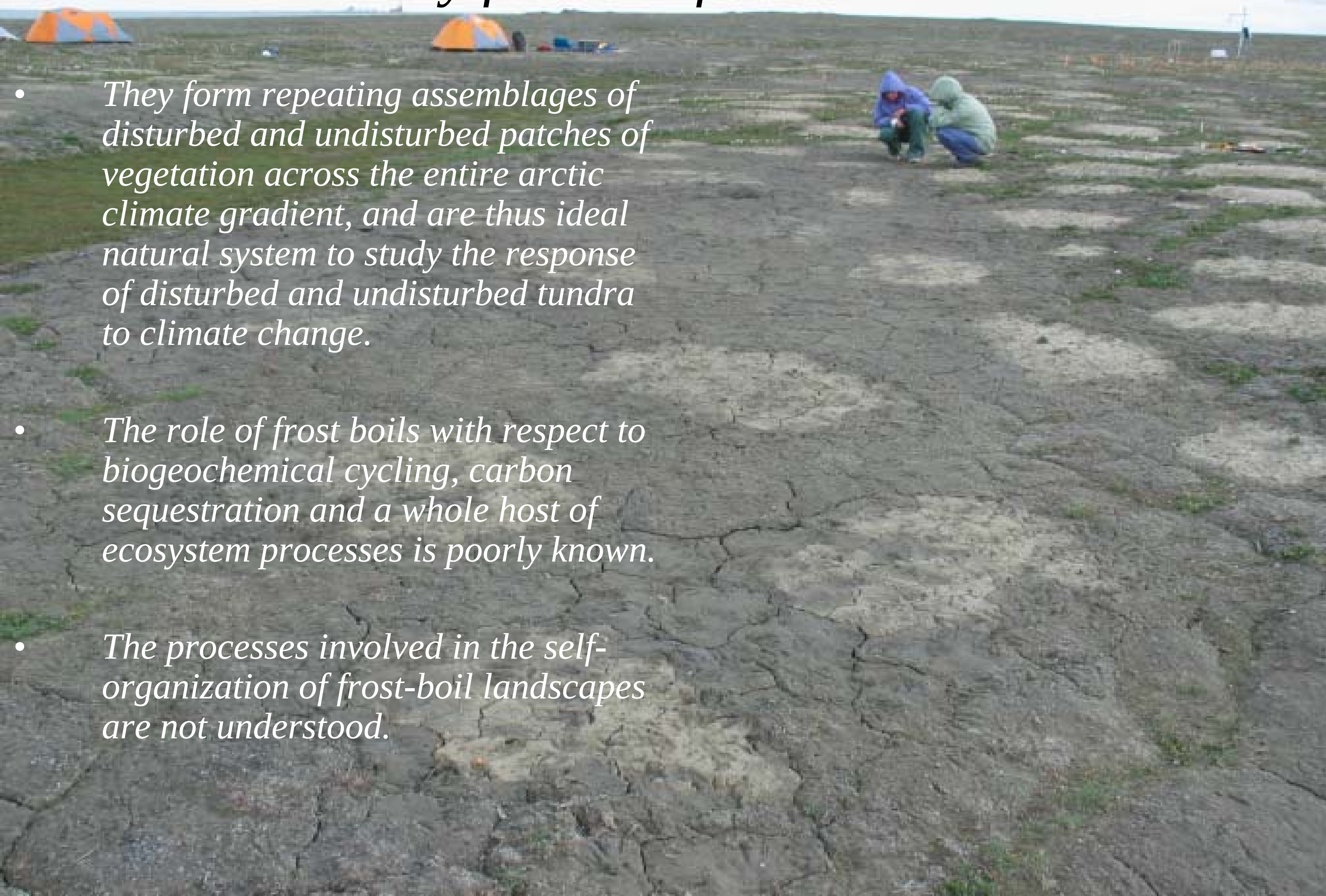
Subzone C, Howe Island, Ak

Frost boil ecosystems: central goal

To better understand the complex linkages between frost heave, biogeochemical cycles, vegetation, disturbance, and climate across the full Arctic summer temperature gradient in order to better predict ecosystem responses to changing climate and land use.

Frost boils Howe Island, Alaska

Why focus on frost boils?



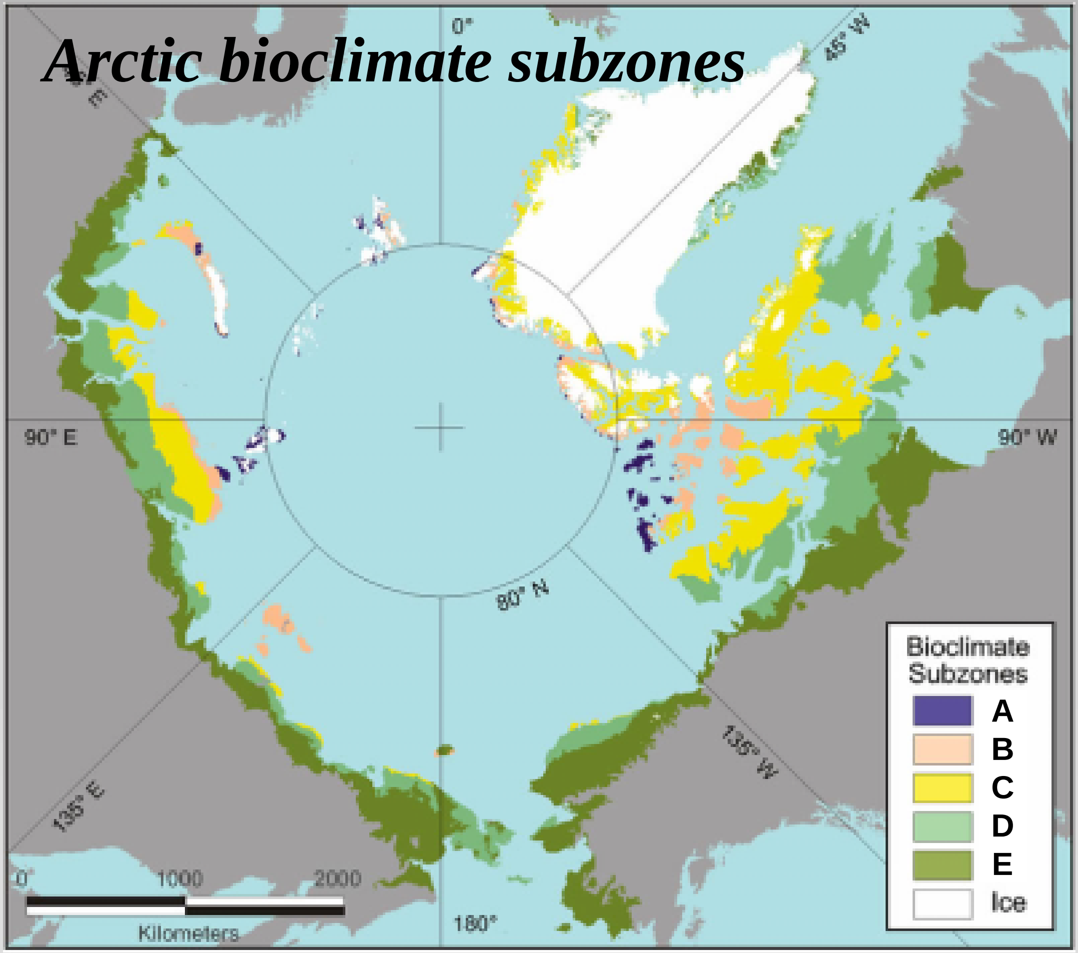
- *They form repeating assemblages of disturbed and undisturbed patches of vegetation across the entire arctic climate gradient, and are thus ideal natural system to study the response of disturbed and undisturbed tundra to climate change.*

- *The role of frost boils with respect to biogeochemical cycling, carbon sequestration and a whole host of ecosystem processes is poorly known.*

- *The processes involved in the self-organization of frost-boil landscapes are not understood.*

Frost boils change their form across the arctic temperature gradient

Sub-zone	*Mean July tempera-ture (˚C)*	*Dominant plant growth forms*
A	2-3	Cushion forbs, mosses, lichens
B	3-5	Prostrate dwarf shrubs
C	5-7	Hemi-prostrate dwarf shrub, sedges
D	7-9	Erect dwarf shrubs, sedges mosses
E	9-12	Low shrubs, tussock sedges, mosses



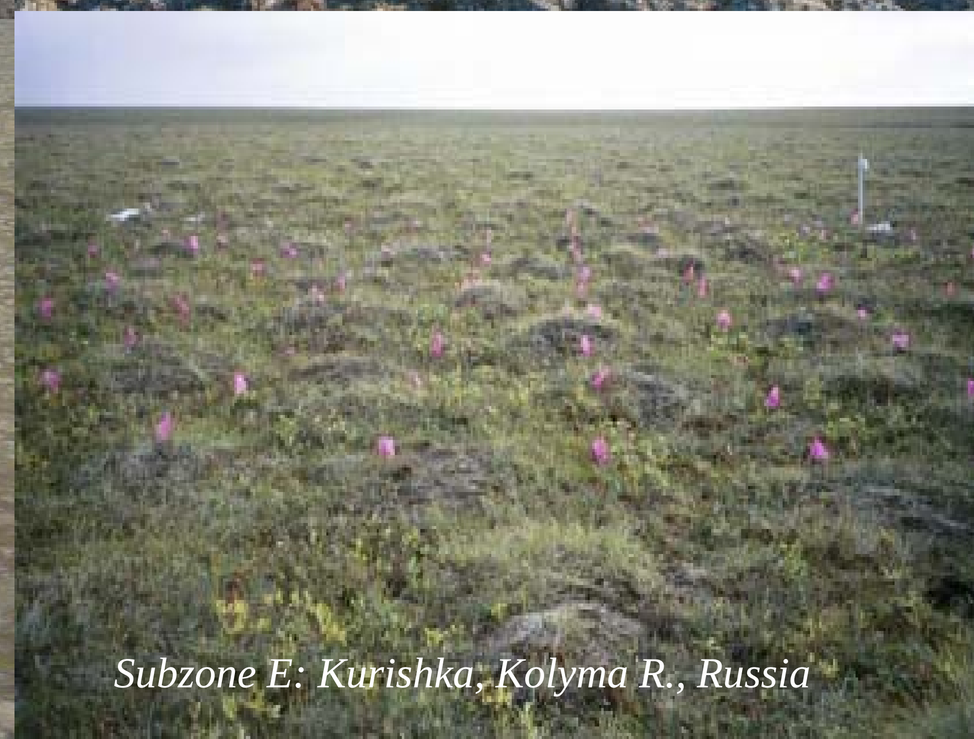
From the *Circumpolar Arctic Vegetation Map*, in press.

Examples of frost boils and hummocks in different climates

Subzone A: Satellite Bay, Prince Patrick I.

Subzone B: Mould Bay, Prince Patrick I.

Subzone C: Bernard R., Banks Island

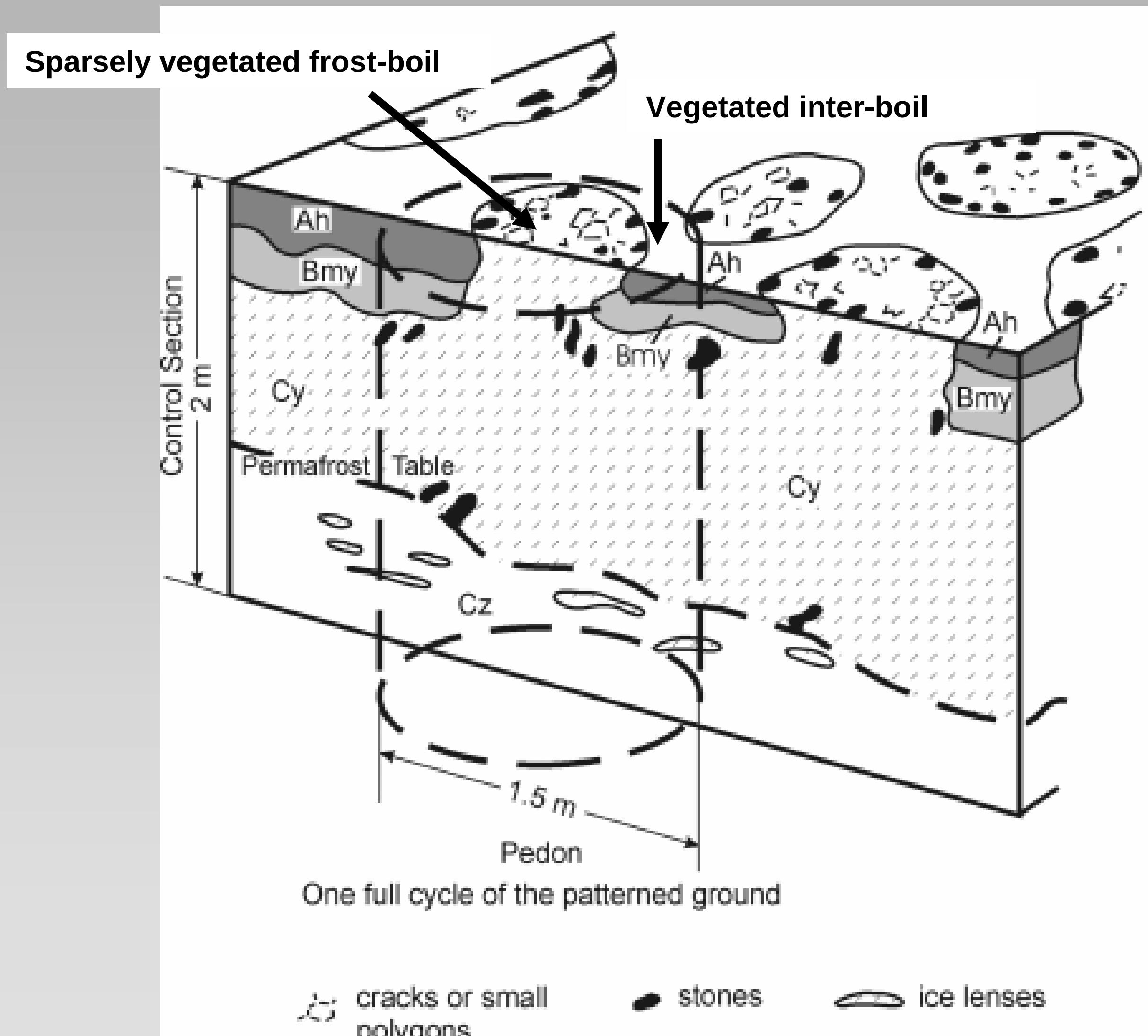


Subzone E: Kurishka, Kolyma R., Russia

Frost-boil Complexity Questions

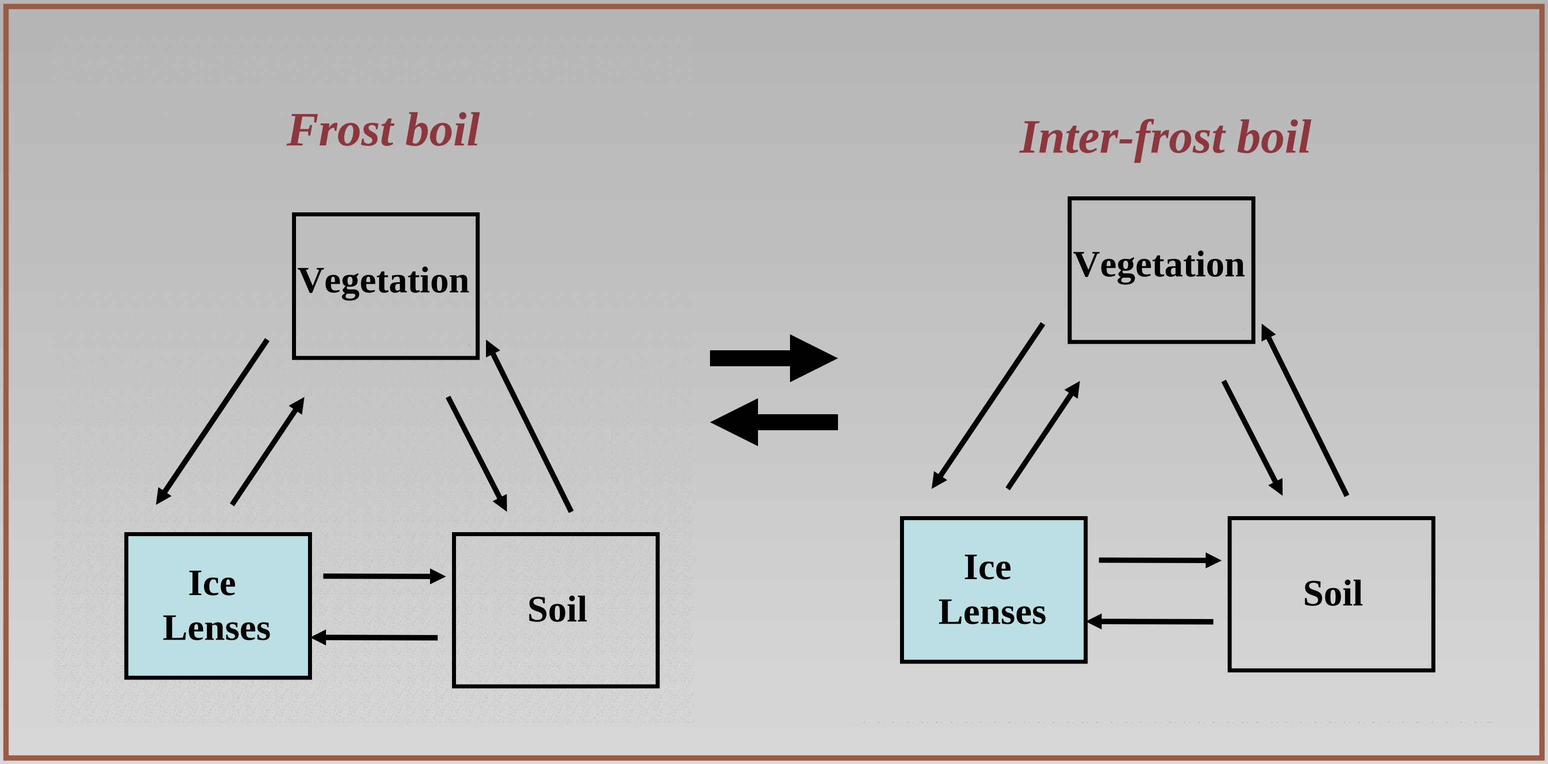
- ***Self organization.***
  - *How do frost boils form?*
  - *How do frost boils organize themselves in concert with the vegetation?*
- ***Complex adaptive systems.***
  - *How do frost-boils and associated ecosystems change along the arctic climate gradient?*
  - *How does the vegetation affect the microclimate, ground ice, disturbance, and soils of frost boils along the Arctic climate gradient?*
- ***Scaling issues.***
  - *What are the emergent properties of frost-boil systems at different scales?*
  - *How do frost boils affect trace gas fluxes, hydrological systems, and patterns of wildlife at large spatial scales?*

The Frost-Boil System



Courtesy of C. Tarnocai

Conceptual Model of the Frost-Boil System

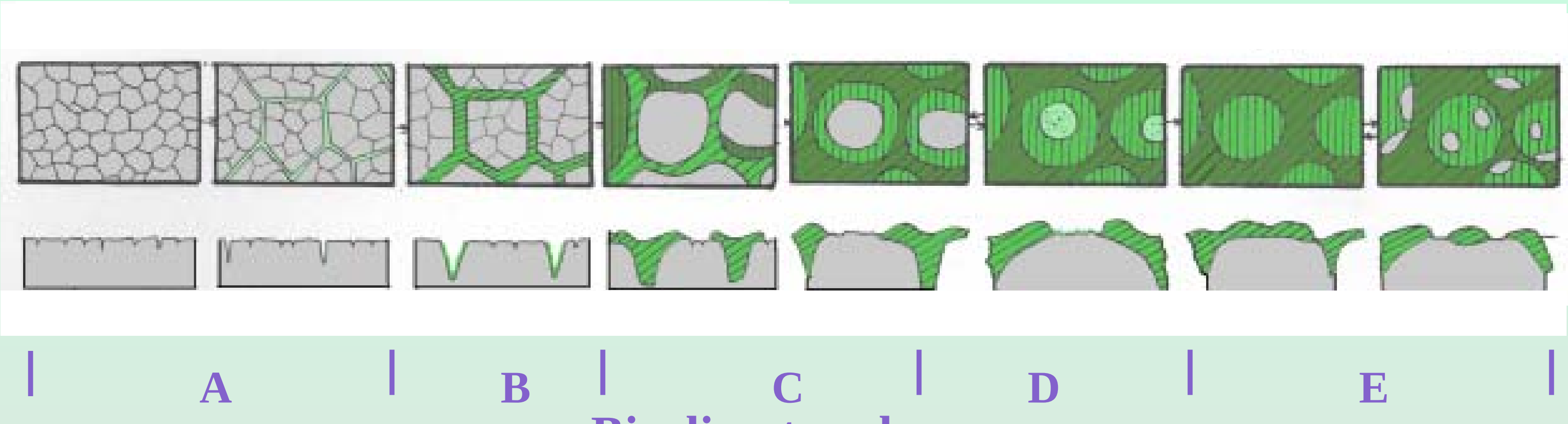


Elements *of the system: Frost boils, inter-boils*

Components *of each element: Ice lenses, soil, vegetation*

Frost-boil/vegetation interactions along the arctic bioclimate gradient

Frost-boil forms

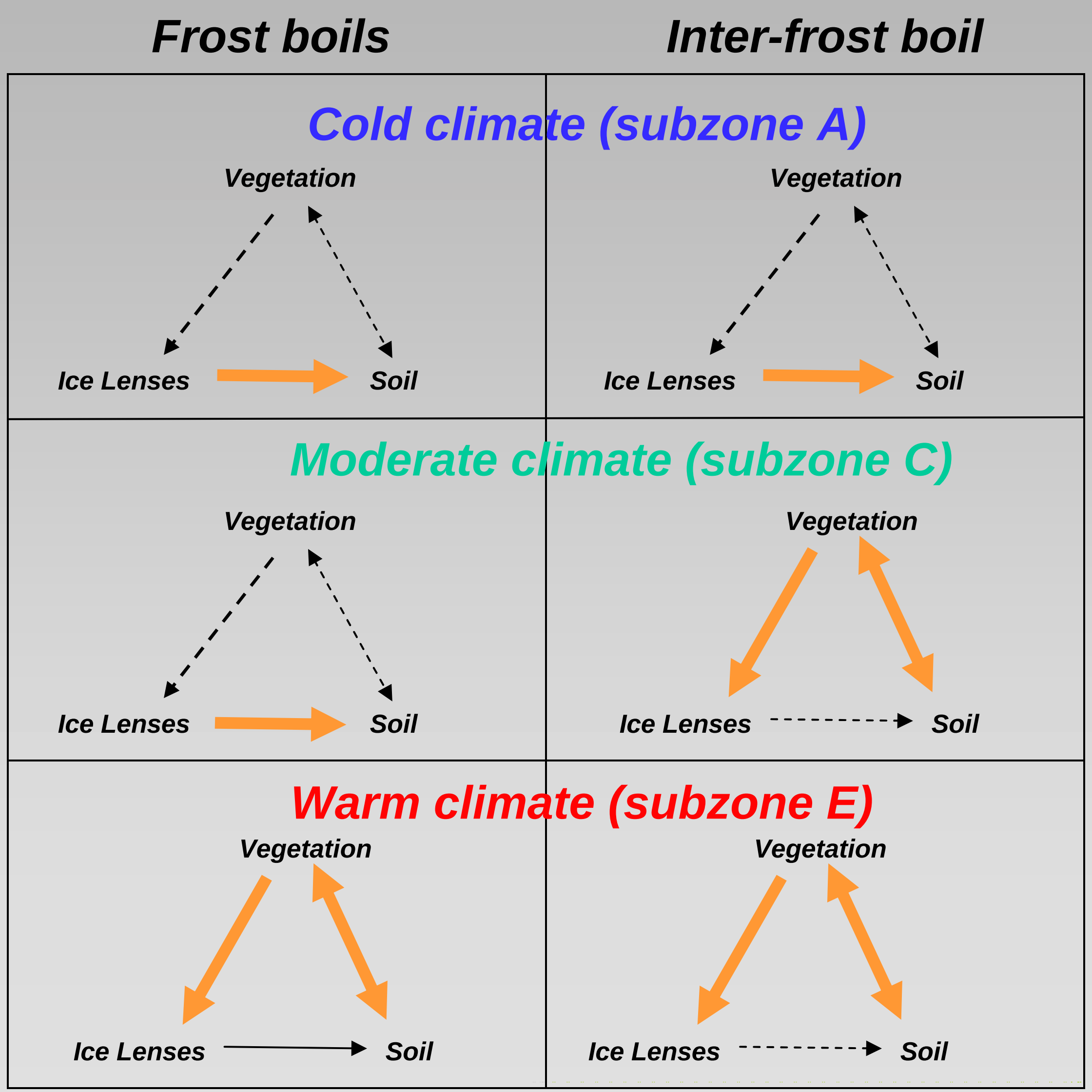


Subzone	Number of polygons per 10 m^2
A	Hundreds?
B	90-150
C	30-60
D	20-30
E	?

- **Increased size and spacing of frost-boils toward the south.**
- **Greatest contrast between the frost-boil and inter-boil areas in Subzones C and northern part of D.**

Modified from Chernov and Matveyeva 1997

Conceptual response of the physical and biological components of the system across the Arctic bioclimate gradient



The Ice Lens Component

• *Ice lenses drive frost heave.*

•*Numerous closely spaced lenses form as the soil freezes downward from the surface.*

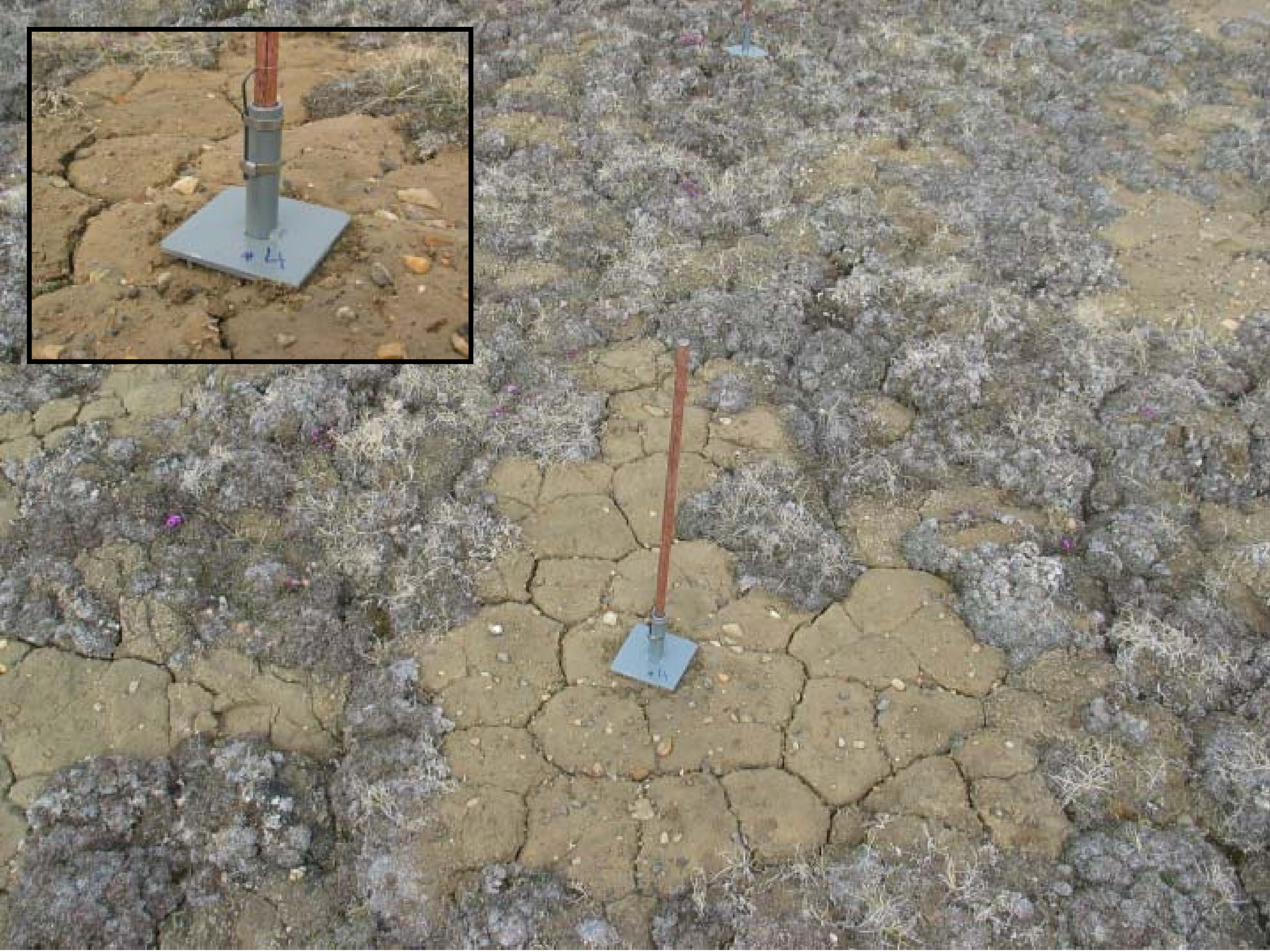
• *The increased volume of the water causes heave.*

• *Heave also is caused by formation of ice at the bottom of the active layer as the soil freezes upward.*

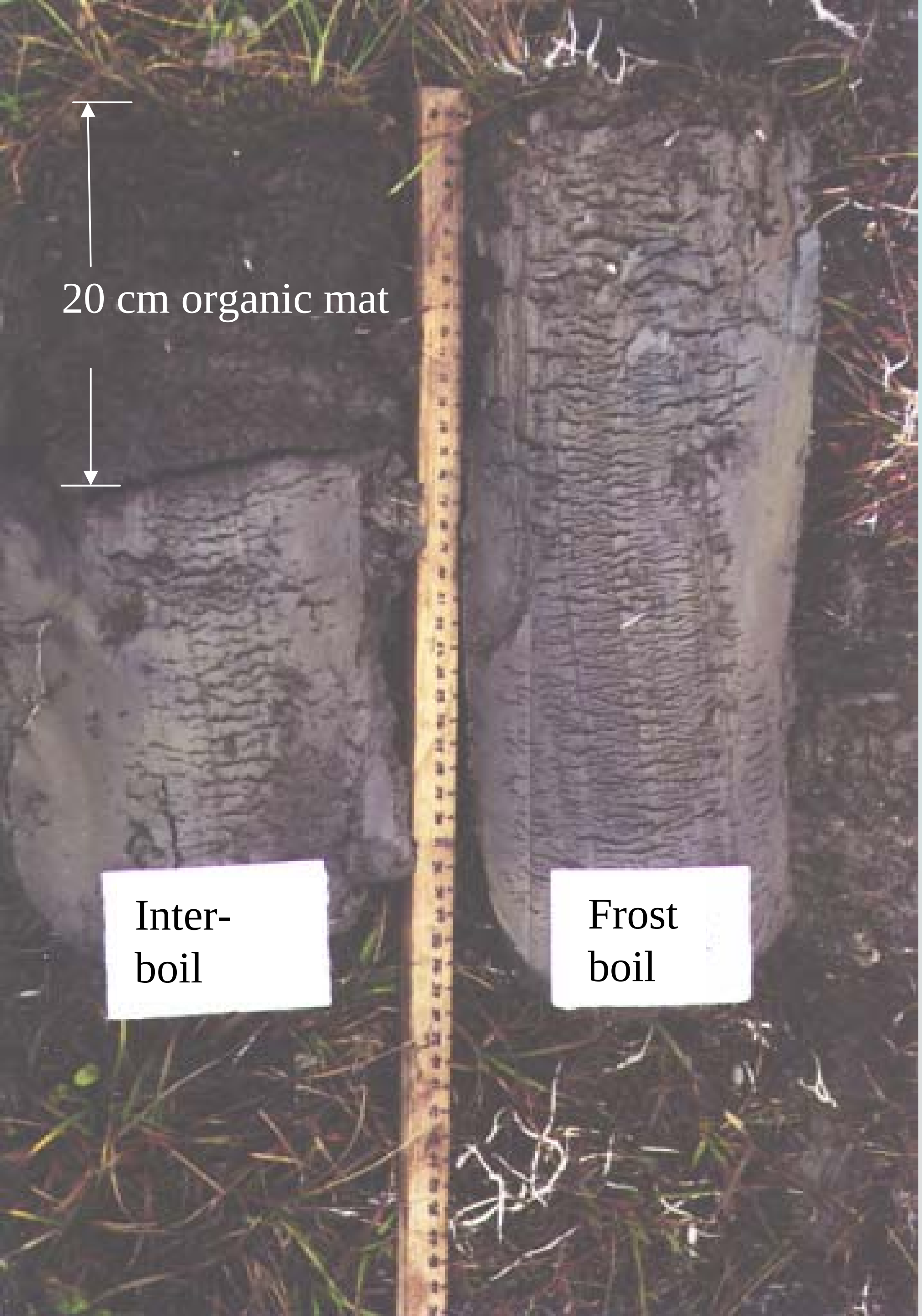
Frozen soil core from a frost boil
Photo Julia Boike

Climate and permafrost research

Vlad Romanovsky


#4

Bill Krantz



Differential frost heave: a function of the number and size of ice-lenses

- *Deep organic layer of inter-frost-boil areas insulates the soil reducing the active-layer thickness and hence the number of lenses and the amount of heave.*

- *Cryostatic suction pulls water from the interboil areas to increase the amount of heave in the frost boil.*

Soil from subzone D near Deadhorse , Alaska
Photo D.A. Walker

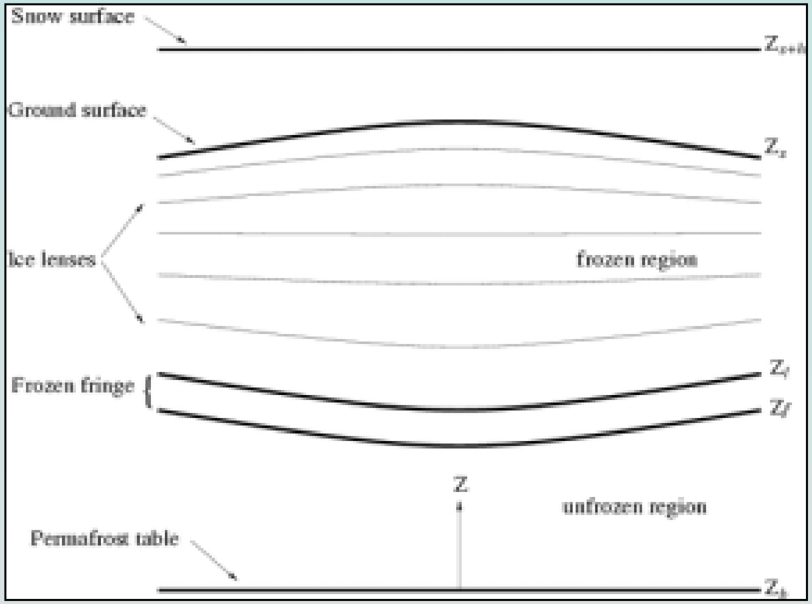
Differential Frost Heave (DFH) model of frost-boil self-organization (Peterson et al. 2003)

- *DFH is a physically based model that provides considerable insight to the self-organization process in frost boils.*

- *Heat preferentially escapes from the surface at high points of small irregularities in the surface. These high points then becomes sites of increased ice-lens development, and more heave.*

- *The spacing of the surface mounds are controlled by mechanical properties of the soil (e.g., texture, active layer thickness).*

- *Theoretically, frost boils should be more closely spaced in shallowly thawed soils.*



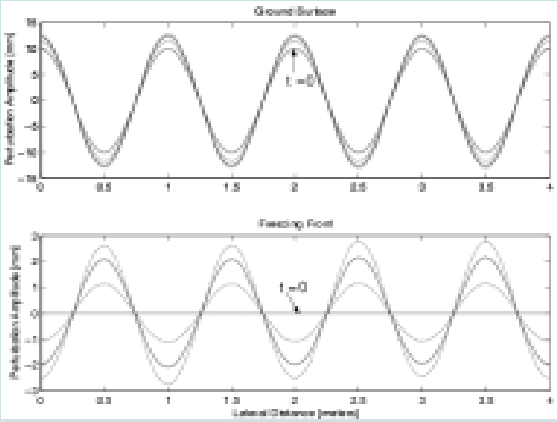
Schematic of soil undergoing top-down freezing. Ice lenses exist in the frozen region and permafrost underlies the active layer.

DFH Model Predictions

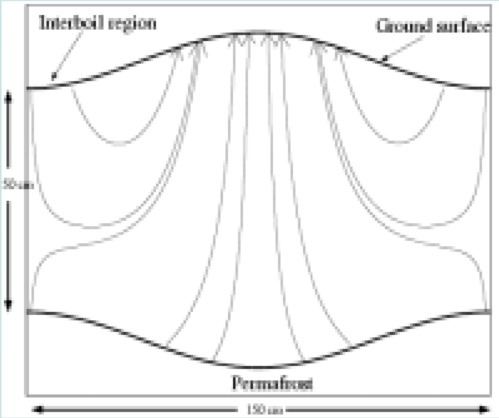
• *The model successfully predicts order of magnitude heave and spacing of frost boils, and can account for the circular motion of soils within the frost boils.*

•*Other predictions include effect of soil texture, air temperature, snow depth on magnitude of heave.*

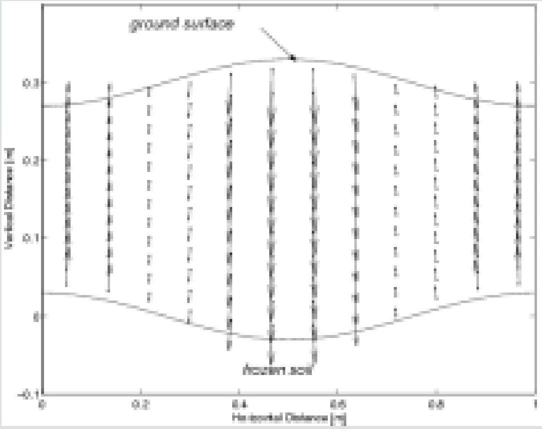
• *Modification of the model is needed to account for the observed variation along the climate gradient that appear to be the result of complex interactions between frost heave and vegetation.*



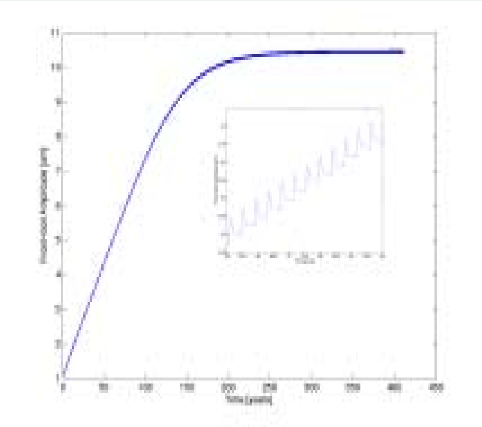
Position of ground surface and freezing fronts



Particle trajectories over several hundred years



Soil creep



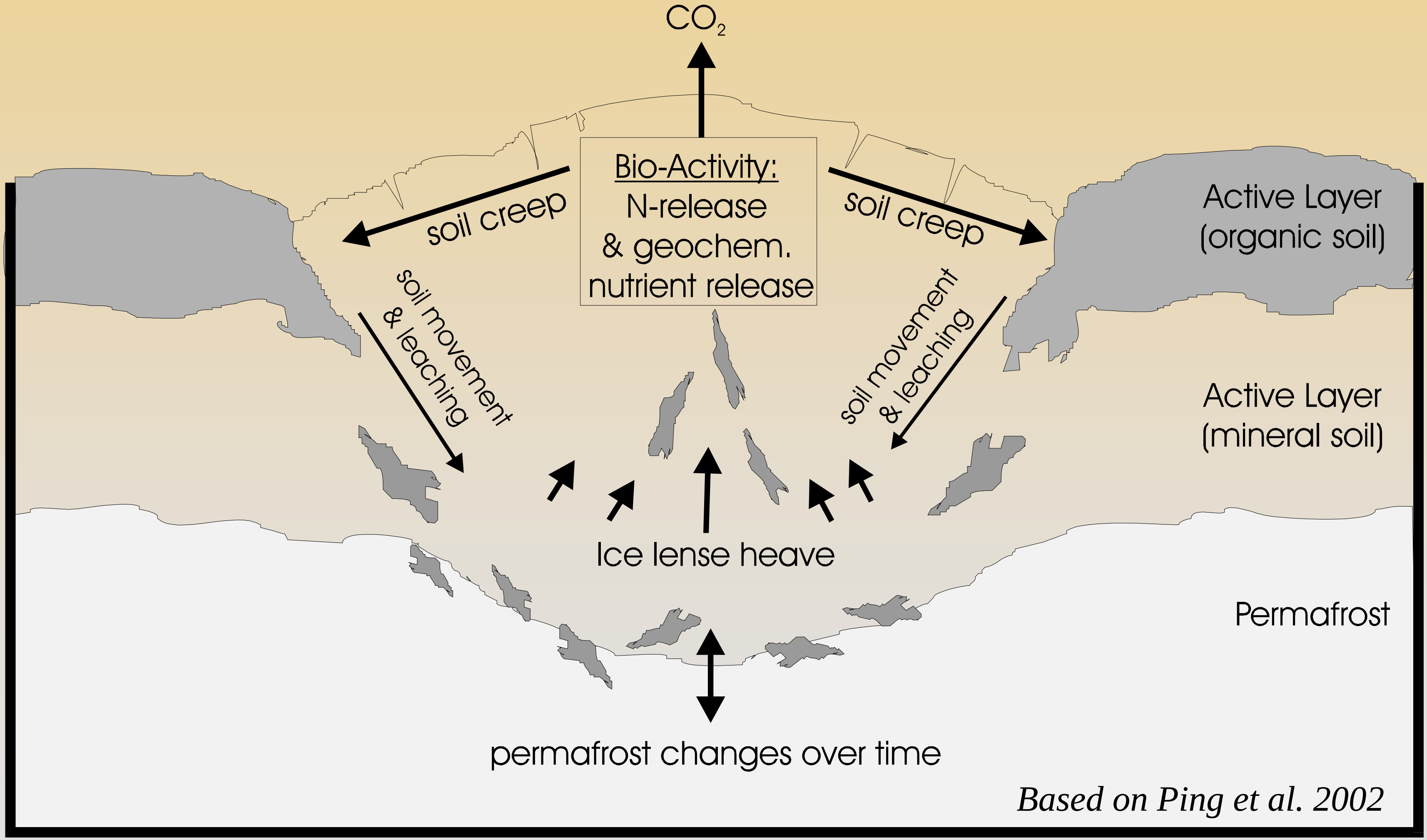
Time to stabilization

Soils component

Chien-Lu Ping and Gary Michaelson

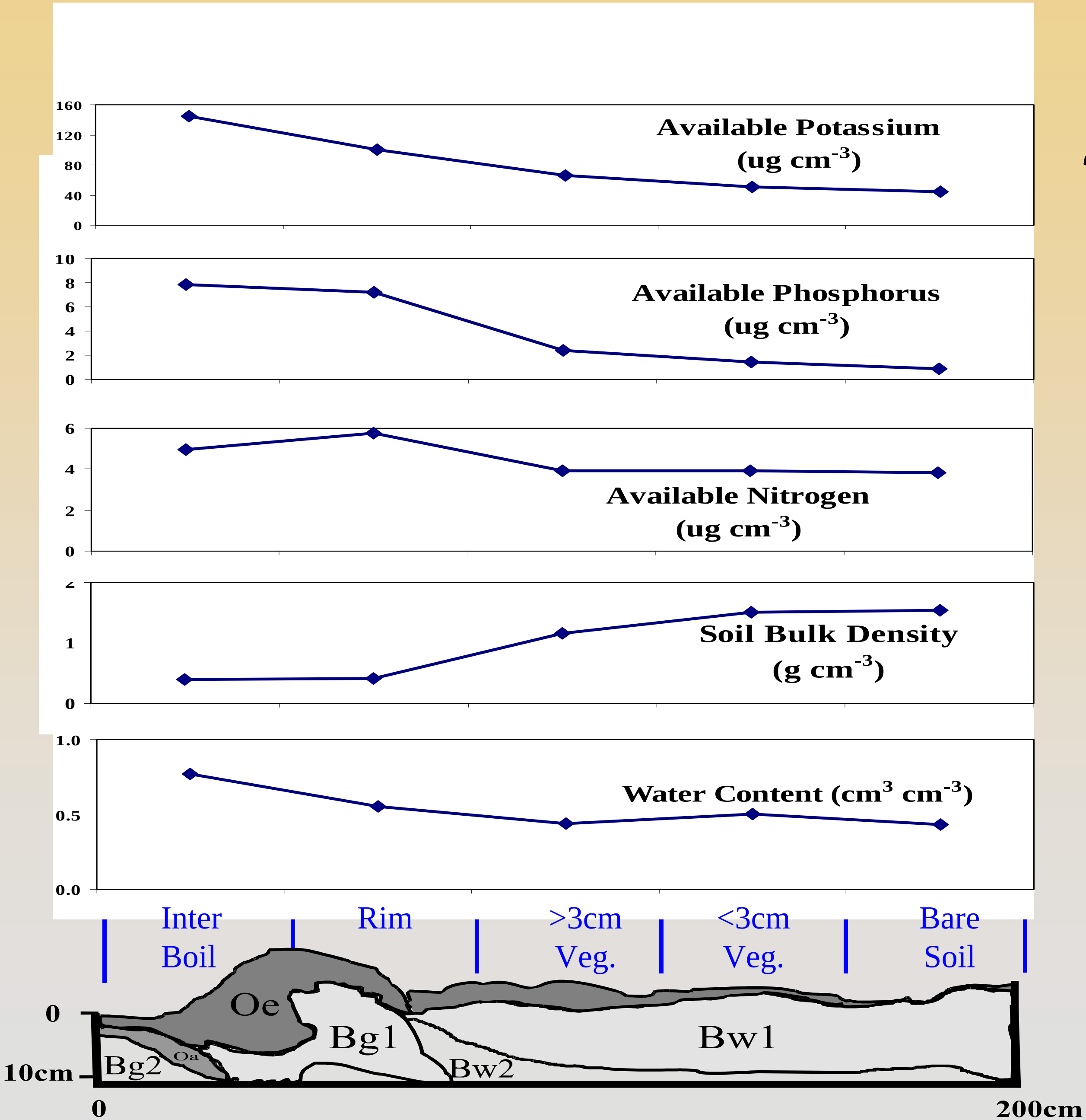
Charles Tarnocai

Biogeochemical cycling and carbon sequestration within frost boils



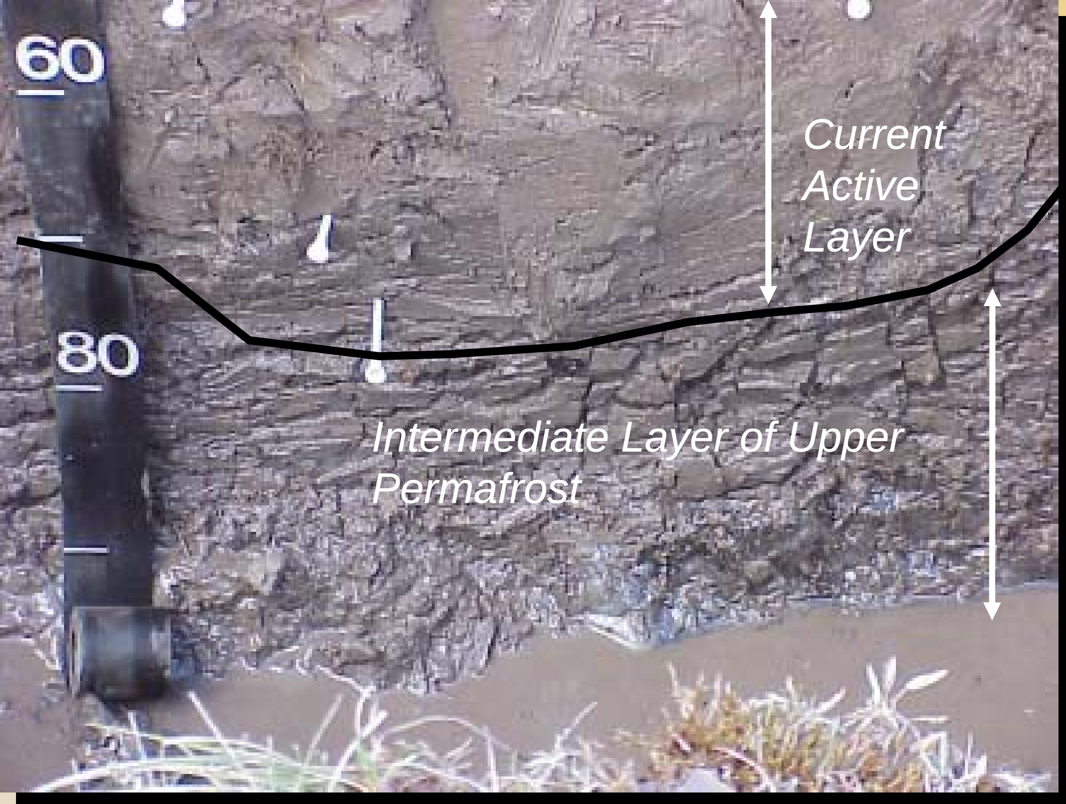
Based on Ping et al. 2002

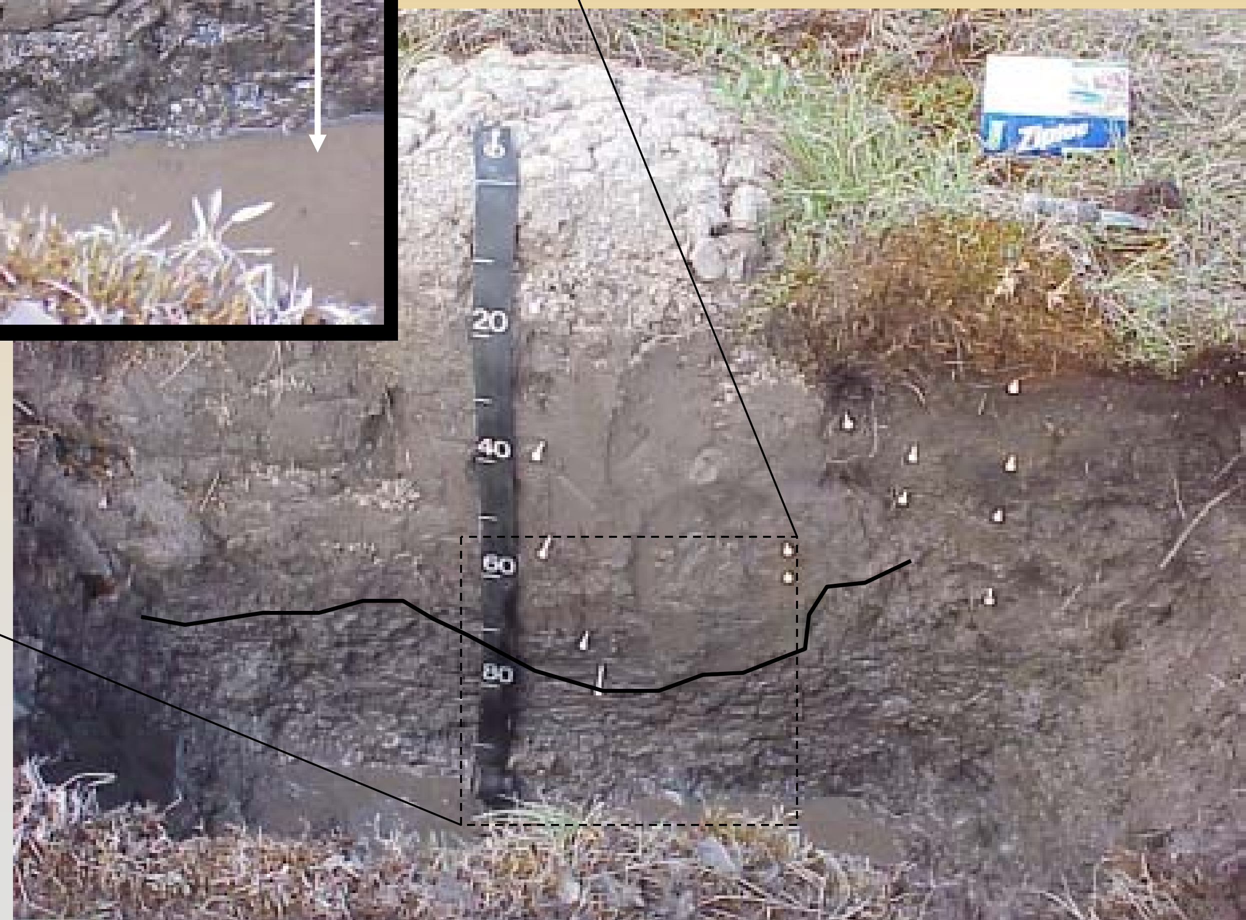
Spatial variation in soil properties across a frost boil,



Cryoturbation of organic material within the frost boil

Buried carbon in the intermediate layer of permafrost table



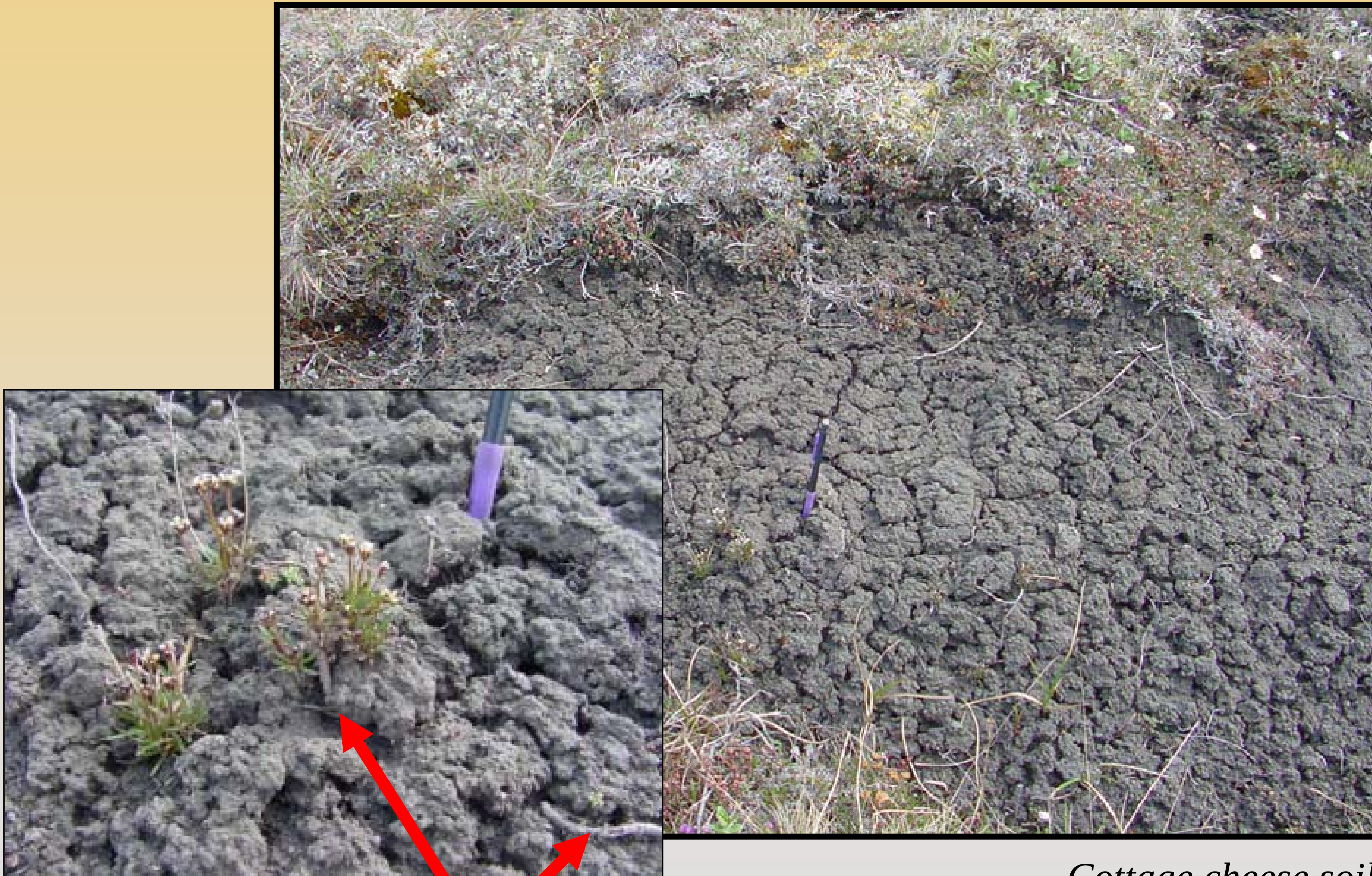


Courtesy of Gary Michaelson

Fine spatial scales: Needle-ice formation (Pipkrakes)

Photos: Outcalt 1971; Davies 2001

Needle-ice consequences

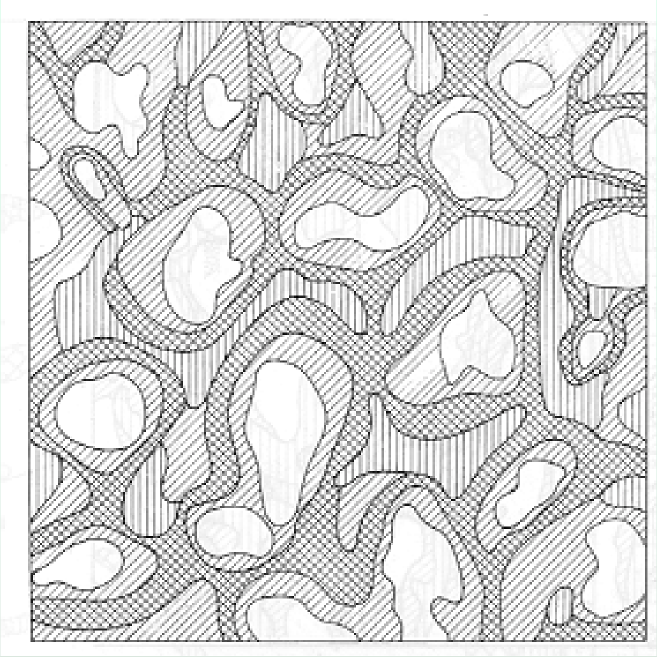


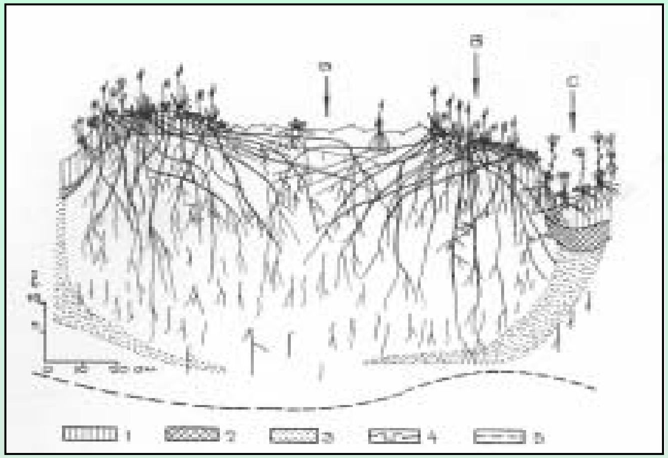
Cottage cheese soil

Braya bartlettiana *and root*

Vegetation component

Vegetation on frost boils





Vertical and horizontal structure of frost-boil plant communities

Matveyeva - Maps of frost boils on the Taimyr Peninsula, Russia

Unique plant species and growth form assemblages

Bill Steere collecting Bryum wrightii *on a frost boil at Prudhoe Bay July, 1971.*

Frost-boil grids

Subzone A:

- Satellite Bay, Canada - 1
- Isachsen, Canada - 0 (+3 planned)

Subzone B:

- Mould Bay, Canada - 1 (+2 planned)

Subzone C:

- Howe Island, Alaska - 1
- West Dock, Alaska - 1
- Green Cabin, Canada - 3

Subzone D:

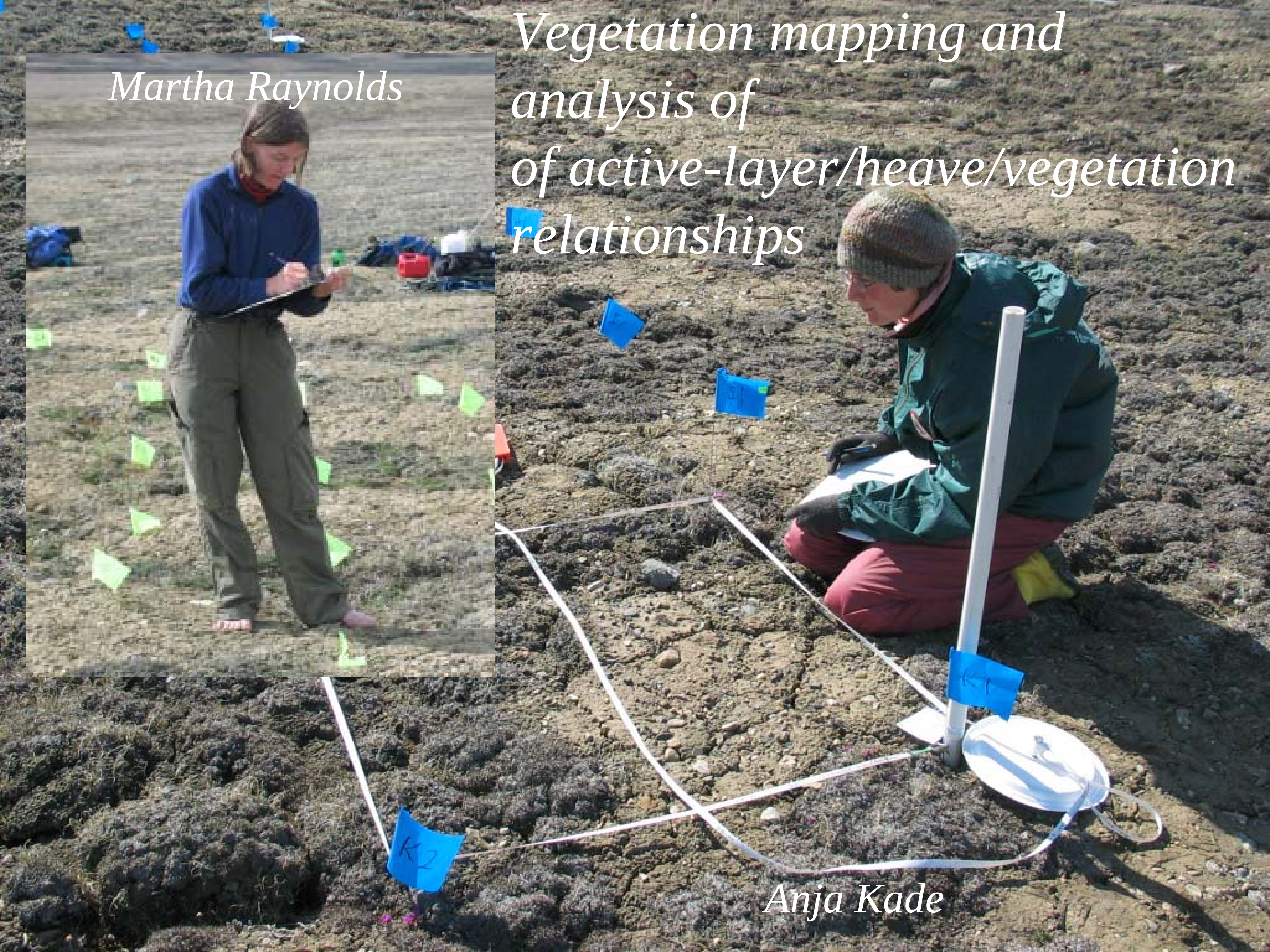
- Deadhorse, Alaska - 1
- Franklin Bluffs, Alaska - 3
- Sagwon MNT, Alaska- 2
- Ambarchik, Russian - 1

Subzone E:

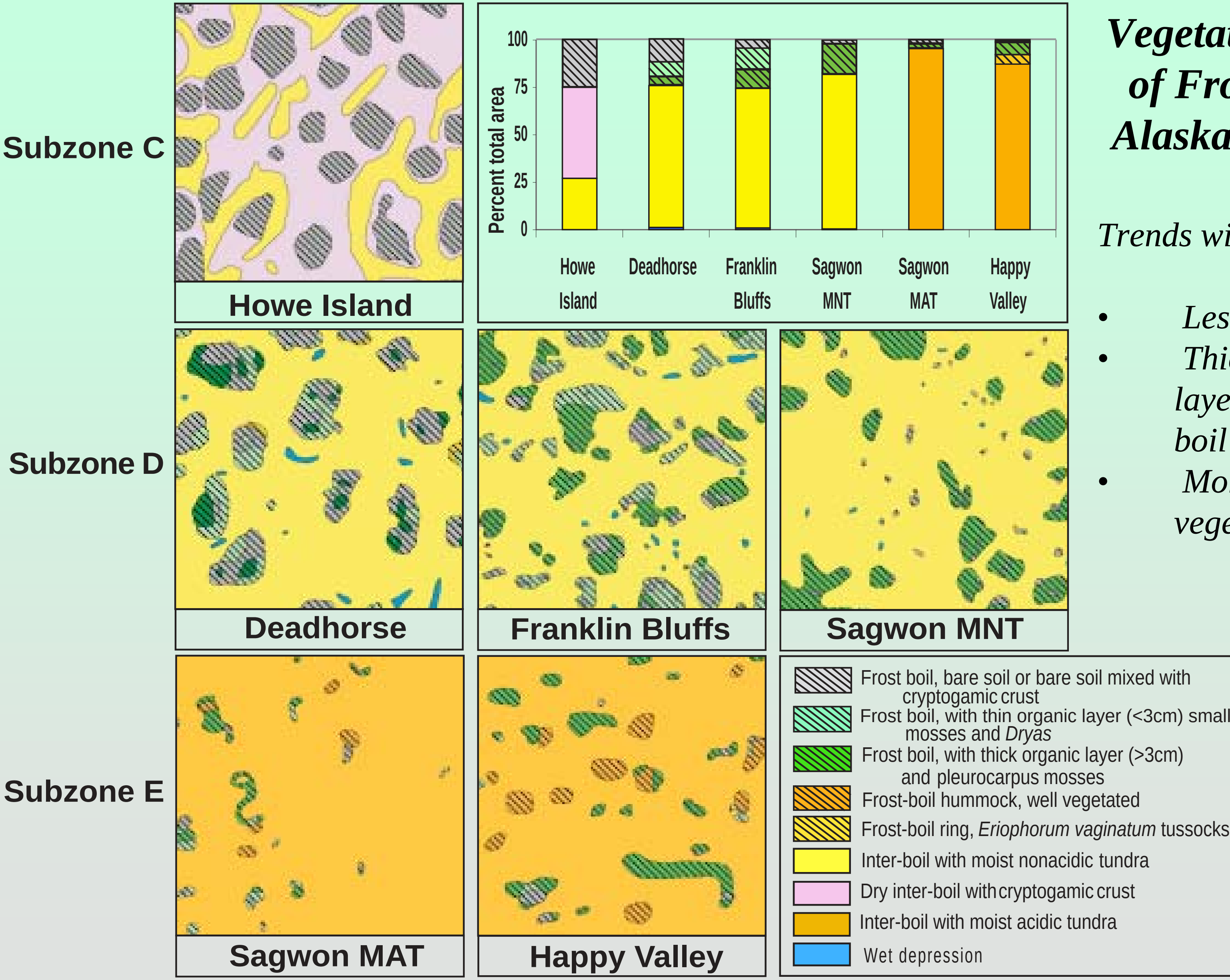
- Sagwon MAT, Alaska - 1
- Happy Valley, Alaska - 3
- Kurishka, Russia - 1

TOTAL 19 (+5 planned) = 24

Happy Valley Grid


Vegetation mapping and analysis of
of active-layer/heave/vegetation relationships
Martha Raynolds
Anja Kade

Vegetation Maps of Frost Boils, Alaska Transect

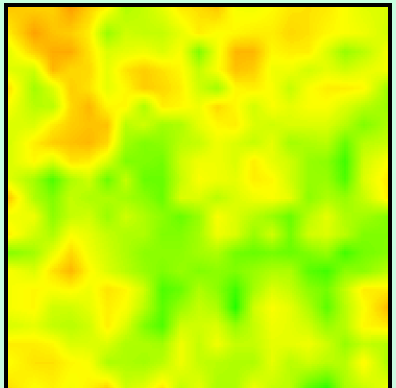


Trends with temperature:

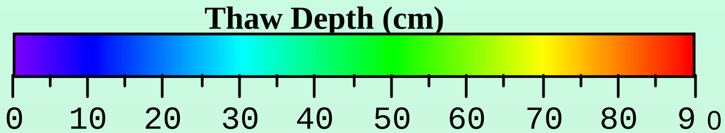
- *Less bare soil*
- *Thicker organic layers in the inter-boil areas*
- *More extensive vegetation mats*

Late-August 2002 thaw depth on the 10x10 m grids, Alaska

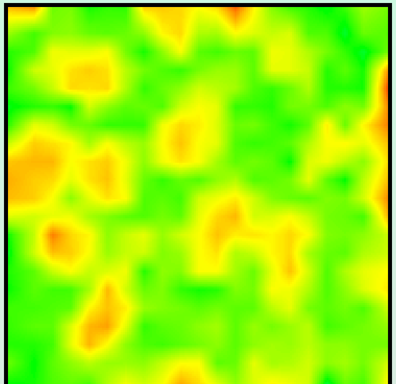
Subzone C



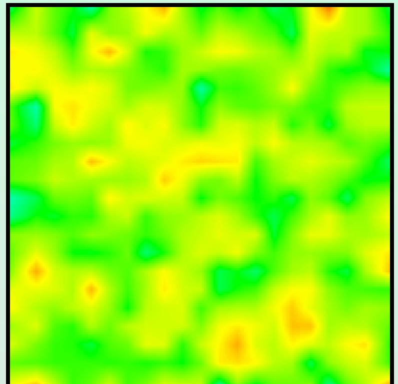
Howe Island



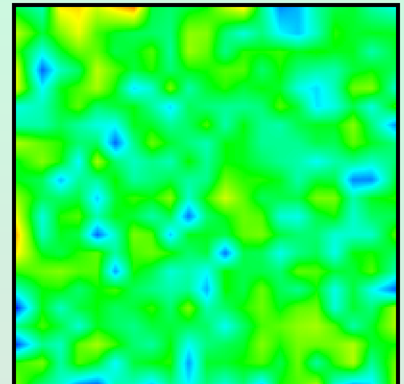
Subzone D



Deadhorse

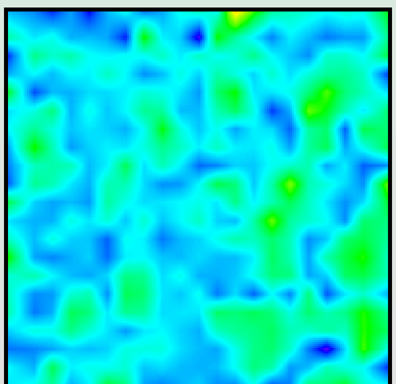


Franklin Bluffs

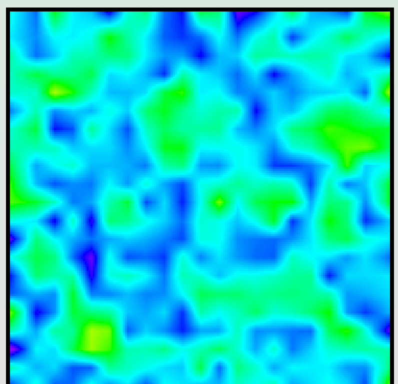


Sagwon MNT

Subzone E



Sagwon MAT



Happy Valley

	Mean Thaw Depth		
Location	Frost box	Inter-boil	Entire Grid
Howe I	70	65	67
West Dock	-	-	25
Deadhorse	70	68	63
Franklin B	66	59	61
Sagwon MNT	48	45	46
Sagwon MAT	46	29	31
Happy Valley	39	29	30

Experimental alteration of vegetation canopy to examine effects of vegetation on active layer and frost heave

Ph.D. project of Anja Kade

Control

Vegetation Removal

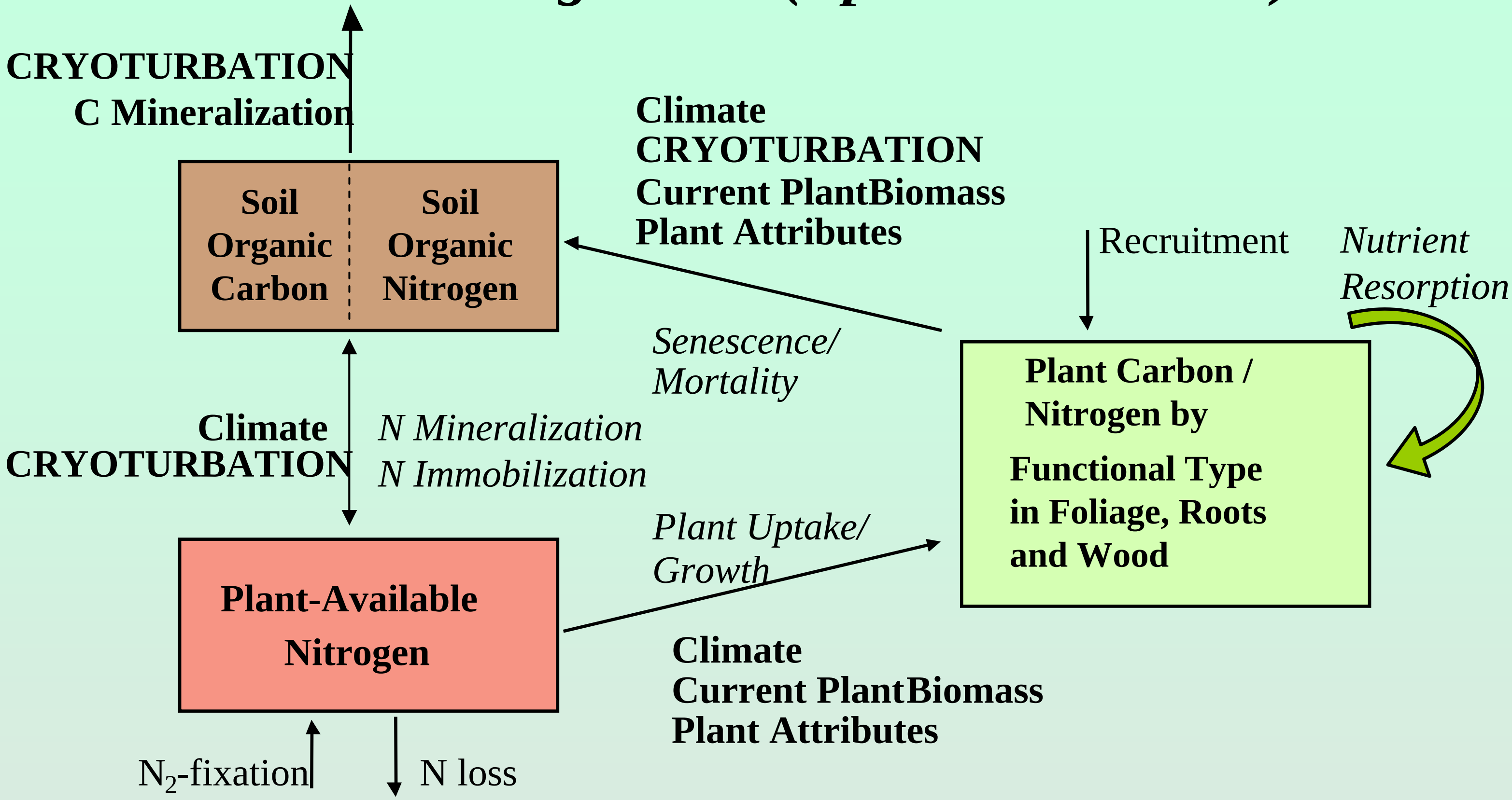
Graminoid Transplants

Moss Carpet Transplants

Response Variables: Frost Heave, Thaw Depth, Soil Moisture, Soil Temperature

Nitrogen Mineralization studies and ArcVeg Model

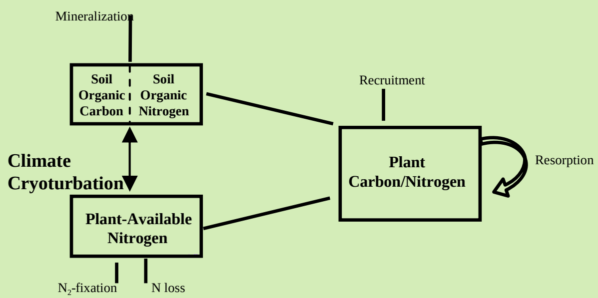
ArcVeg Model (Epstein et al. 2000)



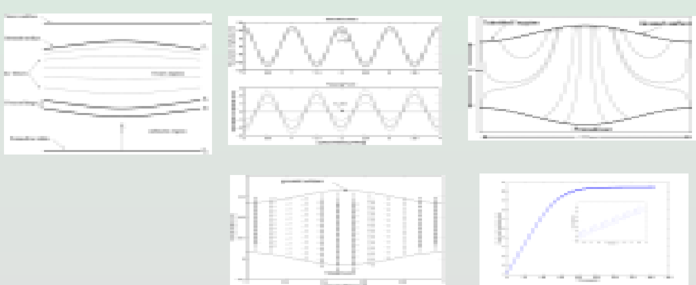
- *Simulates the interannual dynamics of tundra plant community composition and biomass.*
- *Parameterized for up to 20 plant growth forms.*
- *Based on nitrogen mass balance among pools of soil organic and inorganic nitrogen, and live plant nitrogen in live phytomass.*
- *Changes in temperature drive changes in net N mineralization and the length of the growing season and thereby alter the community biomass and composition.*
- *Climate and disturbance are stochastic forcing variables.*

Linking modeling efforts

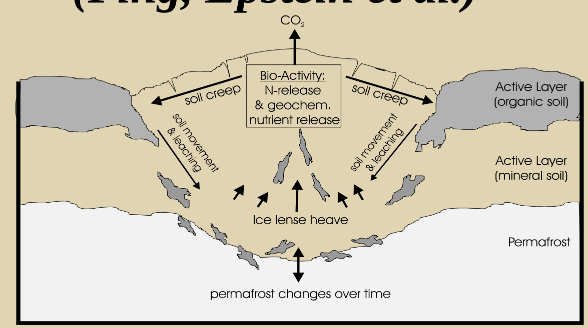
Vegetation Component (Epstein, Walker et al.)



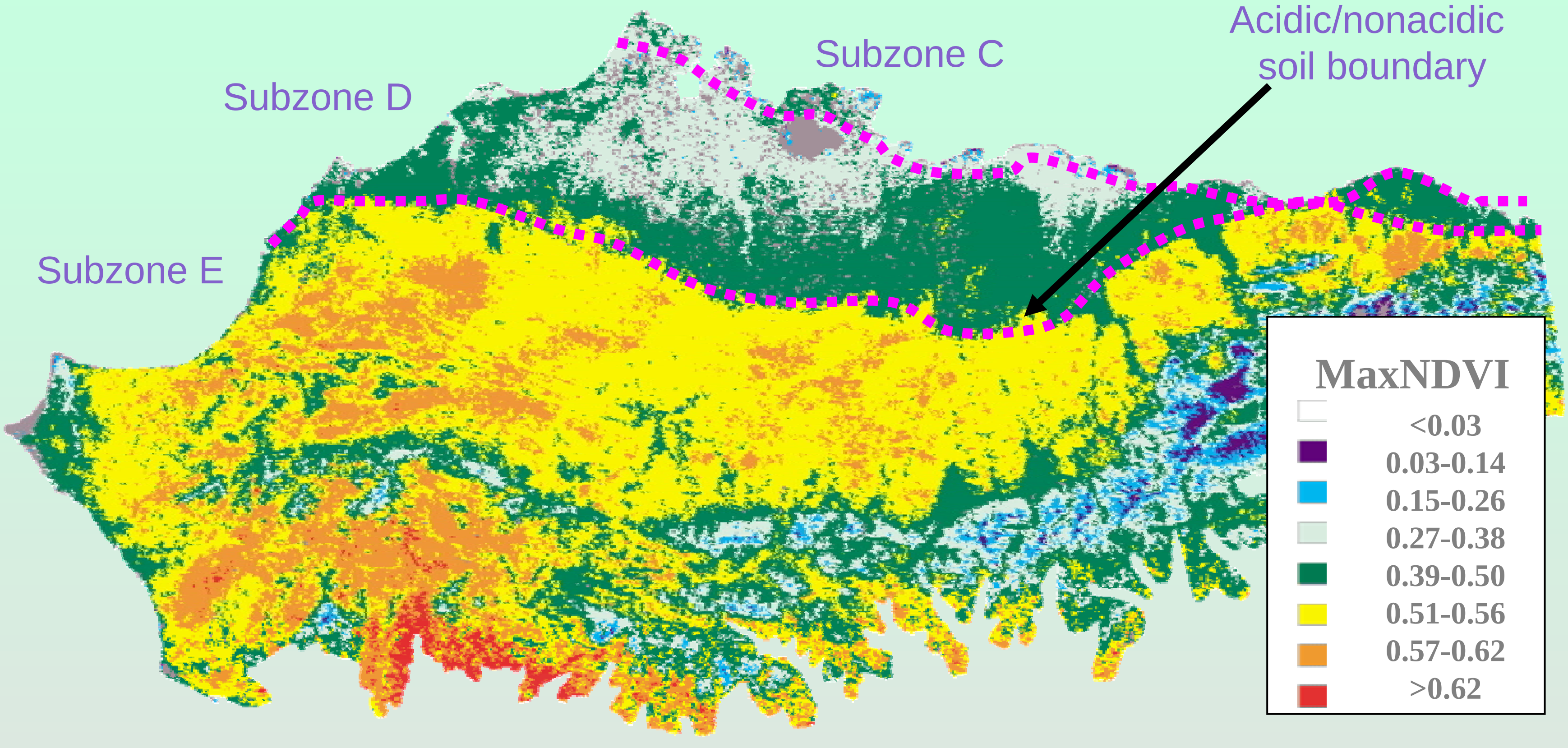
Ice-lens Component (Krantz, Romanovsky, et al.)



Soil Component (Ping, Epstein et al.)



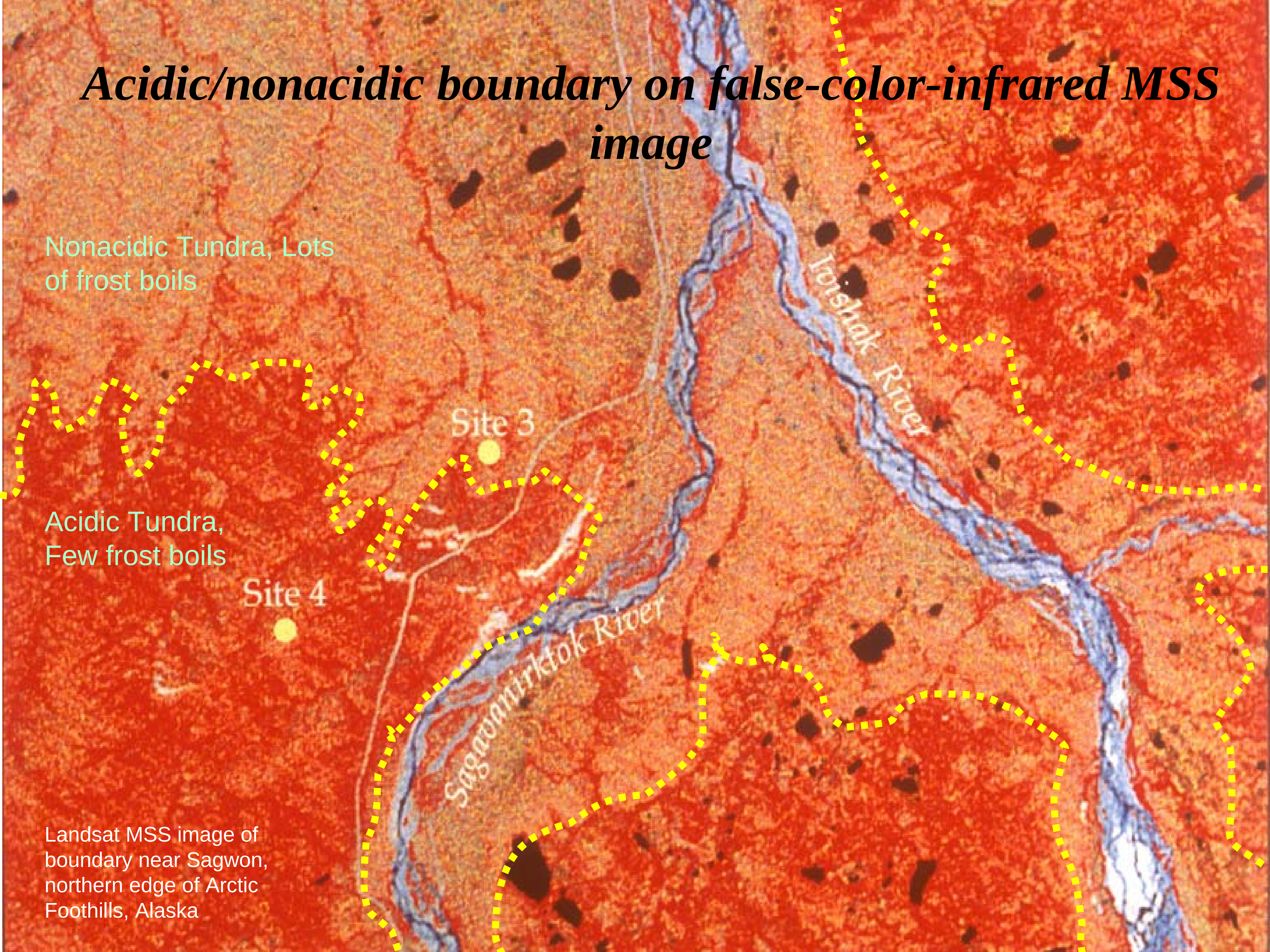
Remote sensing: manifestation of frost boils at regional scales



- ***Boundary between bioclimate subzones C and D corresponds to a major spectral boundary on remotely sensed images.***
- ***North of the boundary:***
  - ***Higher soil pH***
  - ***More frost boils***
  - ***Fewer shrubs, and shorter plants***

Maxium NDVI 1992 and 1995

Acidic/nonacidic boundary on false-color-infrared MSS image



Landsat MSS image of boundary near Sagwon, northern edge of Arctic Foothills, Alaska

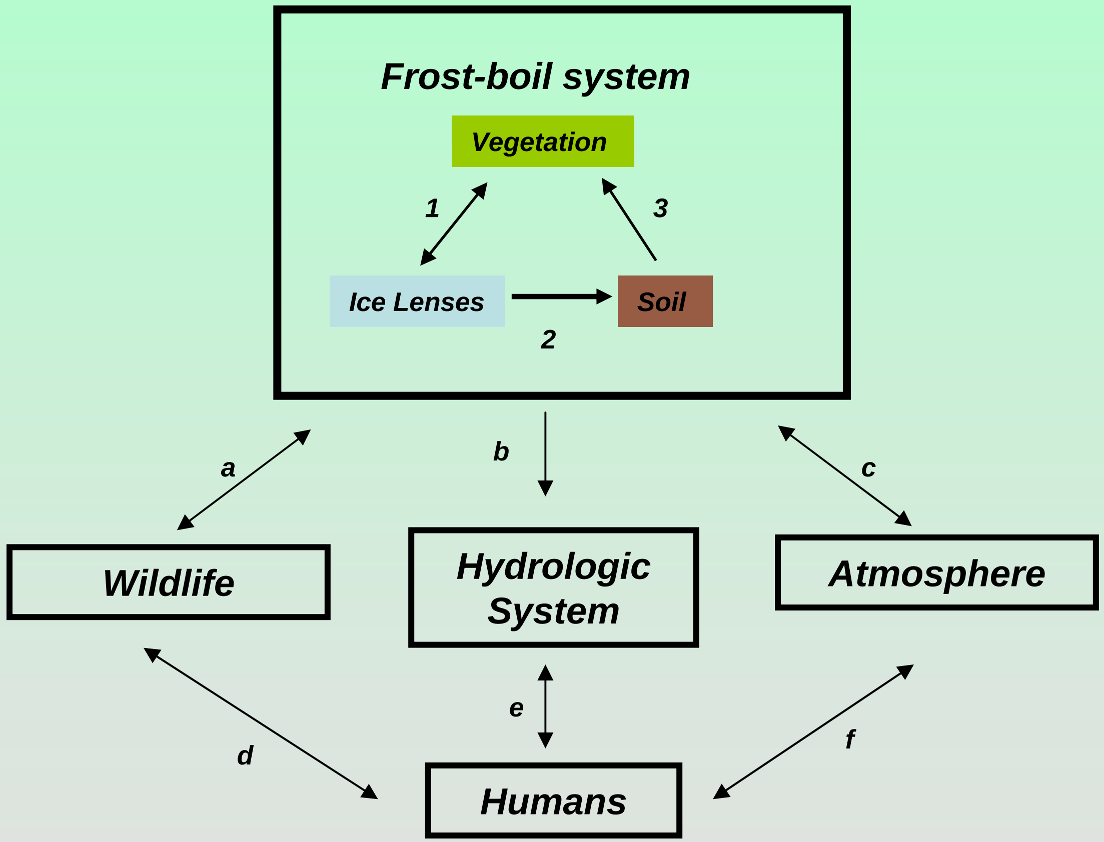
Effects of frost boils on a variety of ecosystem properties

Previous studies suggest that compared to acidic tussock tundra, frost-boil ecosystems have:

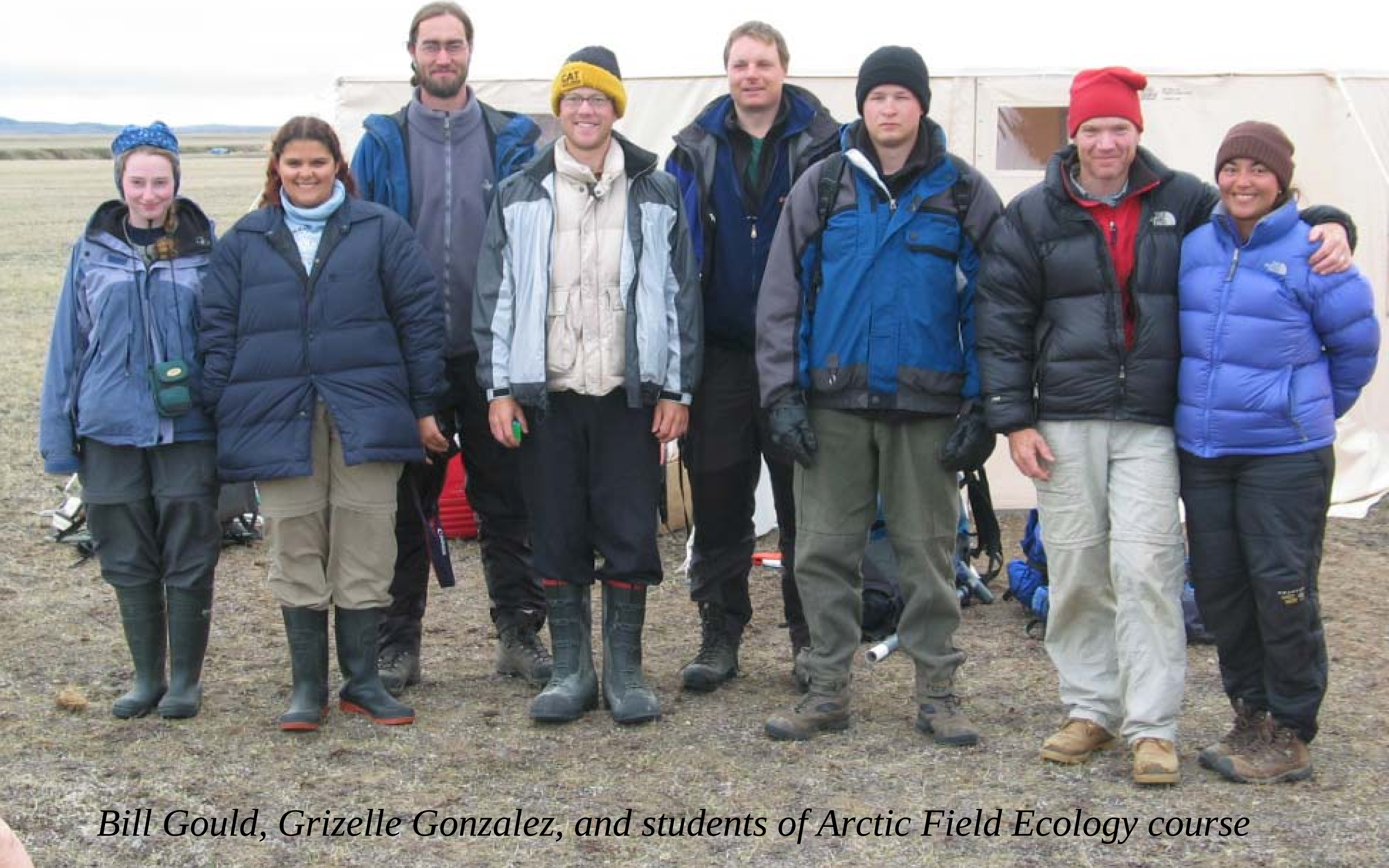
- ***Deeper active layers***
- ***Greater heat flux***
- ***Less CO_2 uptake***
- ***Less methane flux***
- ***More diverse floras***
- ***Less secondary metabolites in the plants***
- ***More nitrogen and calcium in the plants***
- ***Fewer tussocks, thinner moss carpets***

Based on studies by Chapin et al. (1998), Nelson et al. (1998),
and Reeburgh et al. (1998), Walker et al. (1998), Gough et al. (2000)

Linkages between the frost-boil system and components of the greater Arctic system and biosphere



Education component

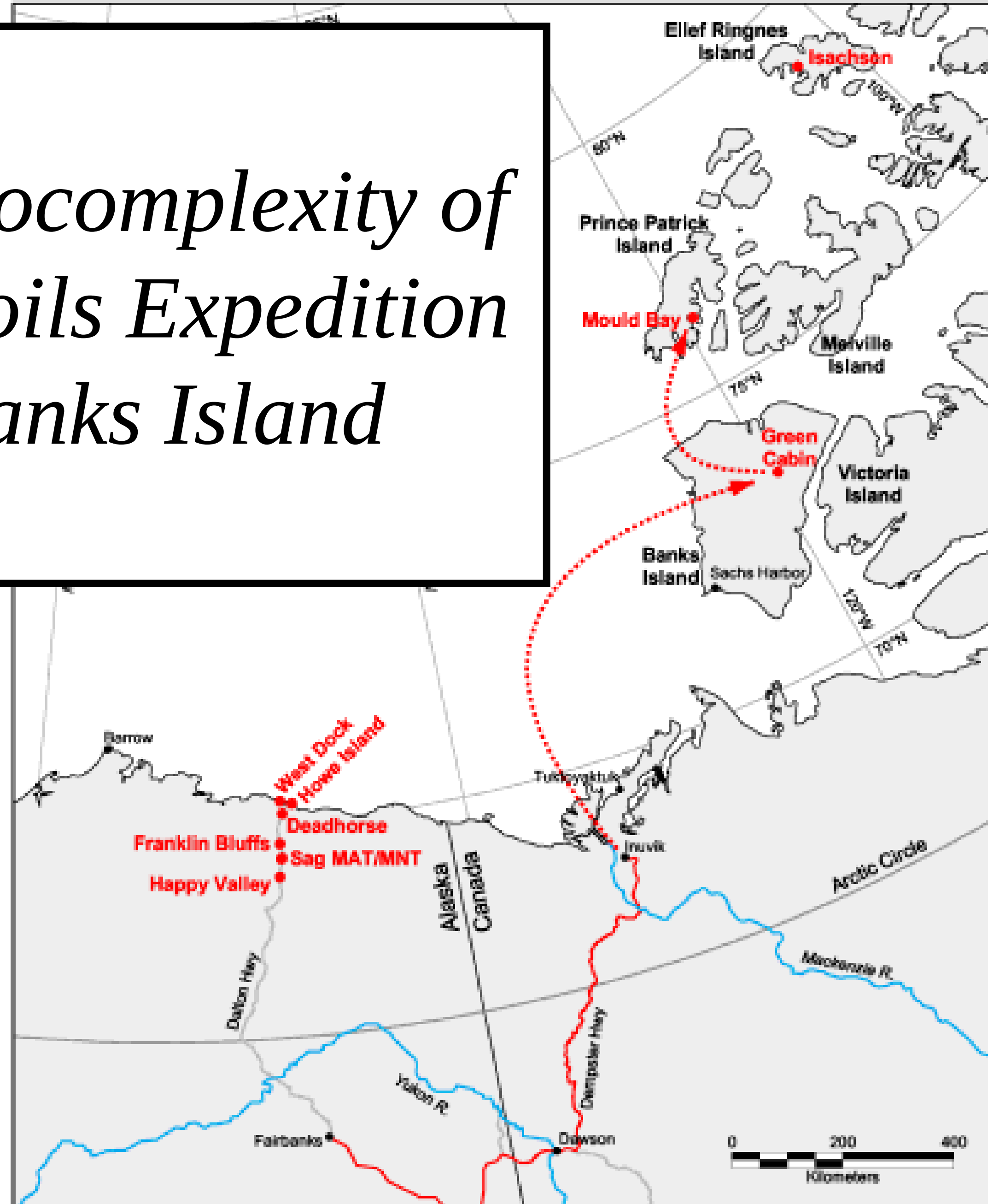


Bill Gould, Grizelle Gonzalez, and students of Arctic Field Ecology course

Photo: Heather Fuller

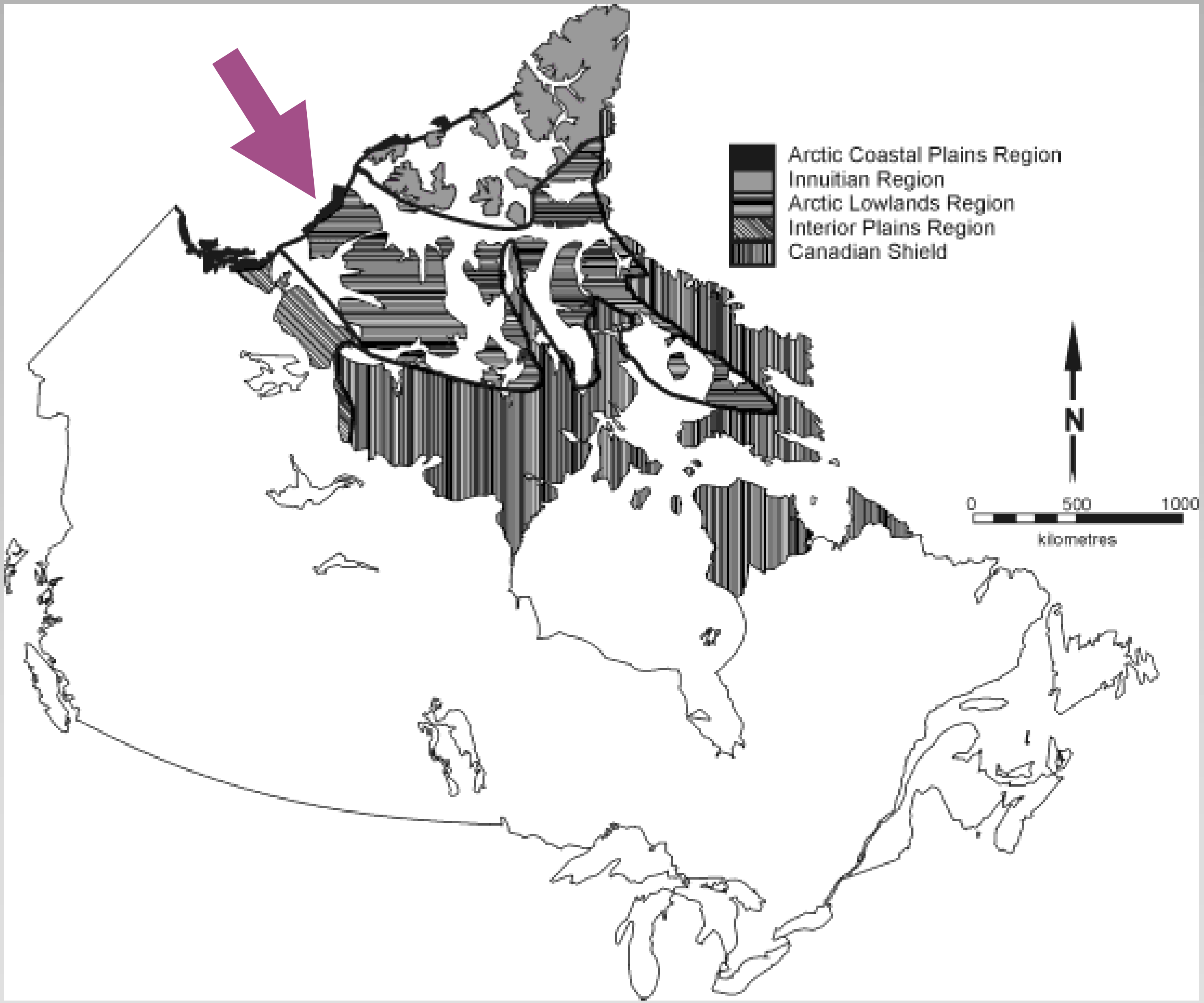



2003 Biocomplexity of Frost-boils Expedition to Banks Island

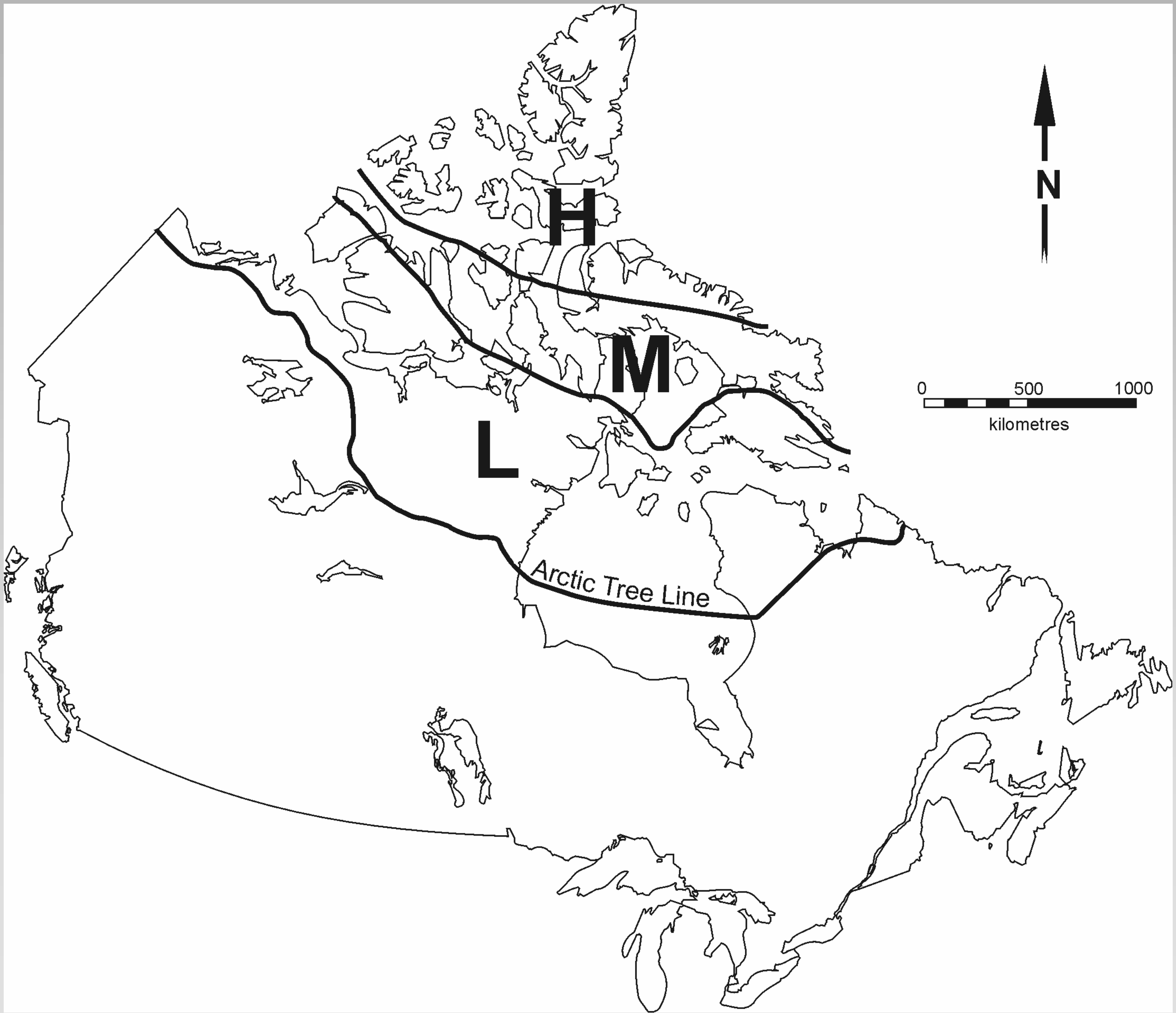



Borek Air Ltd.

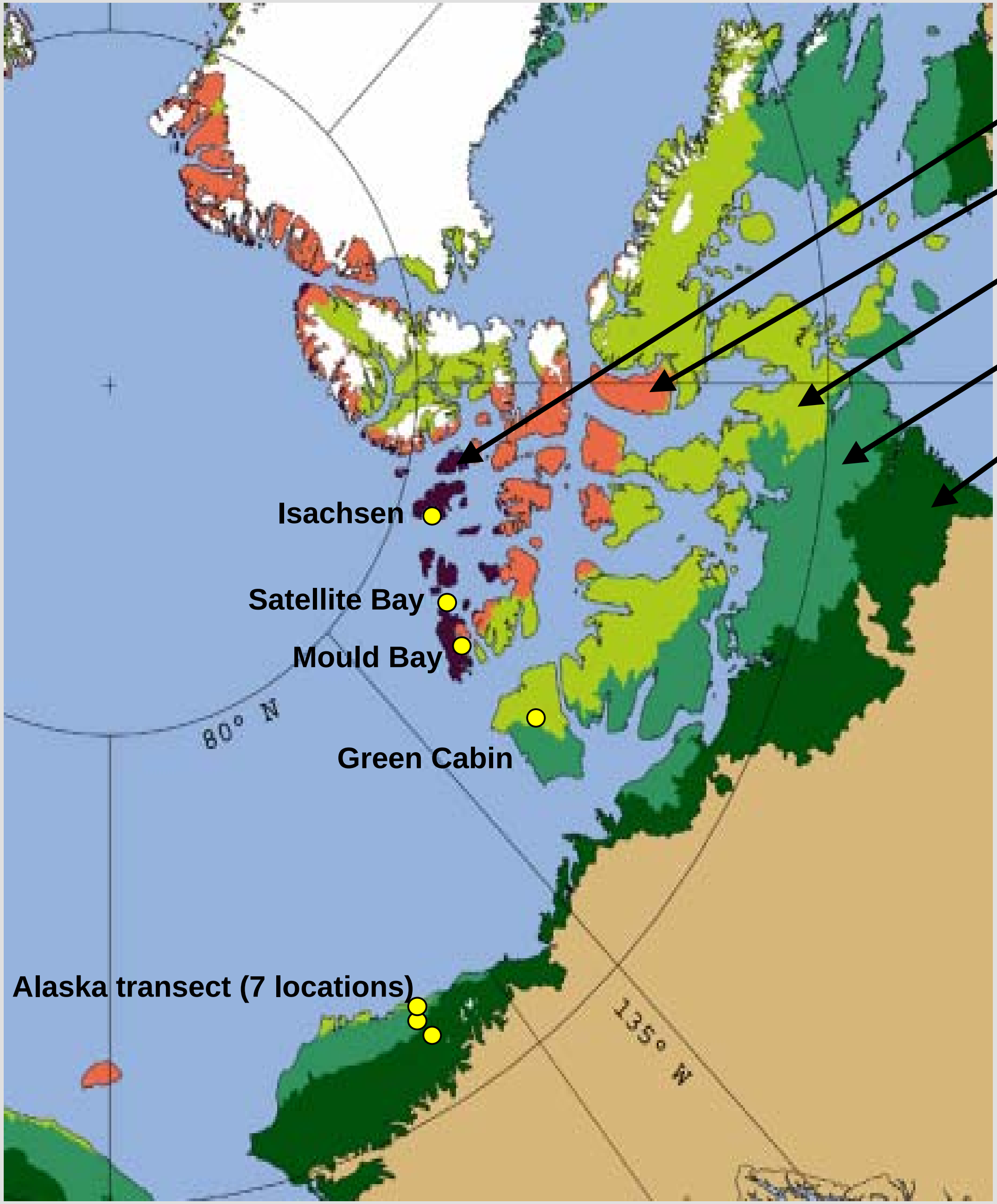
Banks Island is in the Arctic Lowlands Physiographic Region.



Northern Banks Island is in the Middle Arctic of Polunin (1951).



And Bioclimate Subzone C of the Circumpolar Arctic Vegetation Map



Subzone A

Subzone B

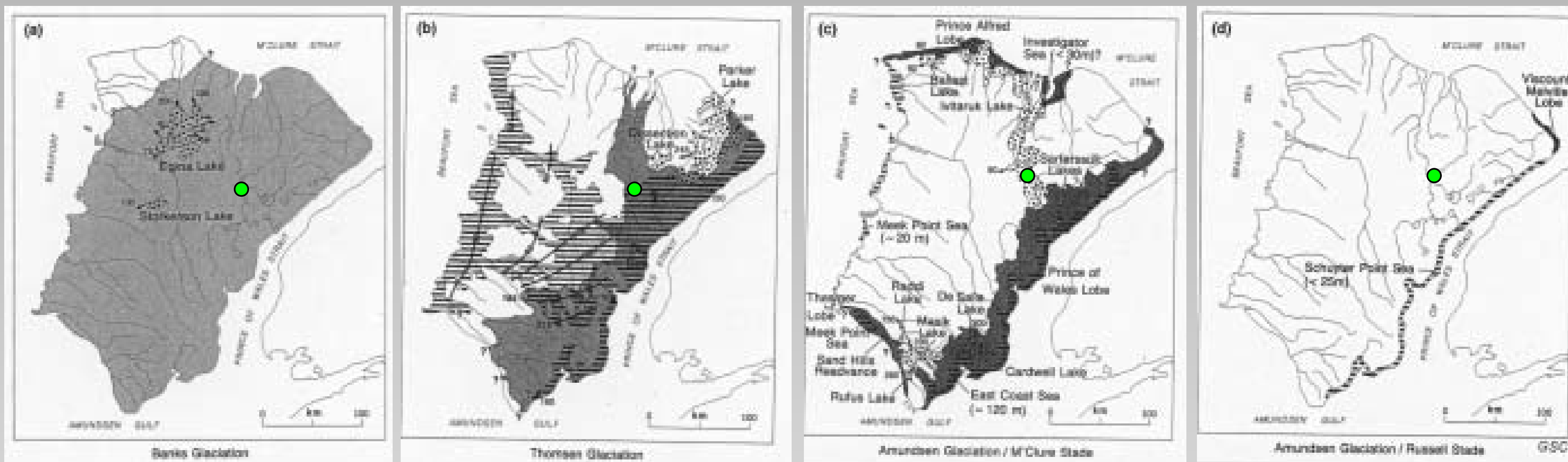
Subzone C

Subzone D

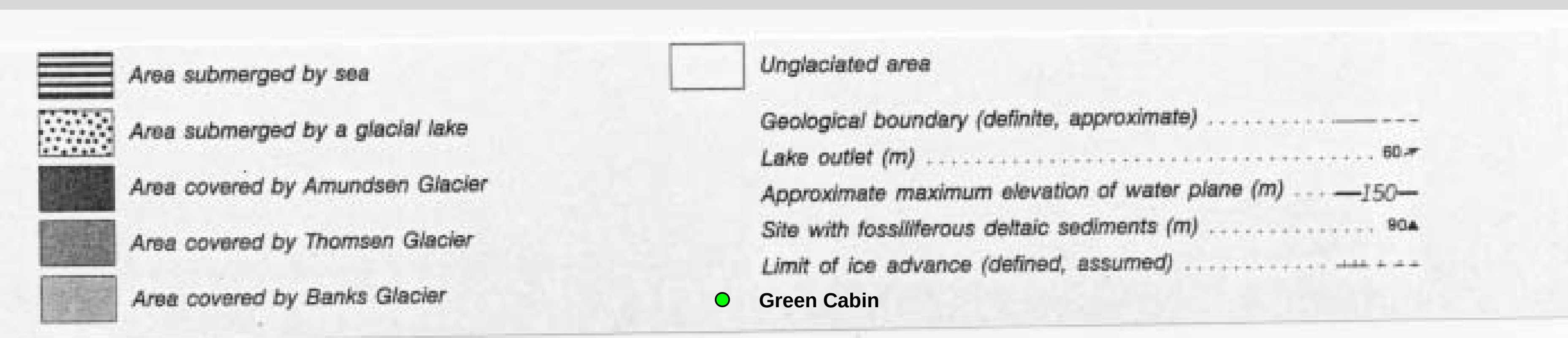
Subzone E

Quaternary Glaciation of Banks Island

Early Pleistocene Banks Glaciation (>790,000 yr)	*Middle Pleistocene Thomsen Glaciation (790-120,000 yr)*	*Early Wisconsinan McClure Stade of Amundsen Glaciation (ca 65,000 yr)*	*Late Wisconsinan Russell Stade of Amundsen Glaciation (ca 13,000 yr)*



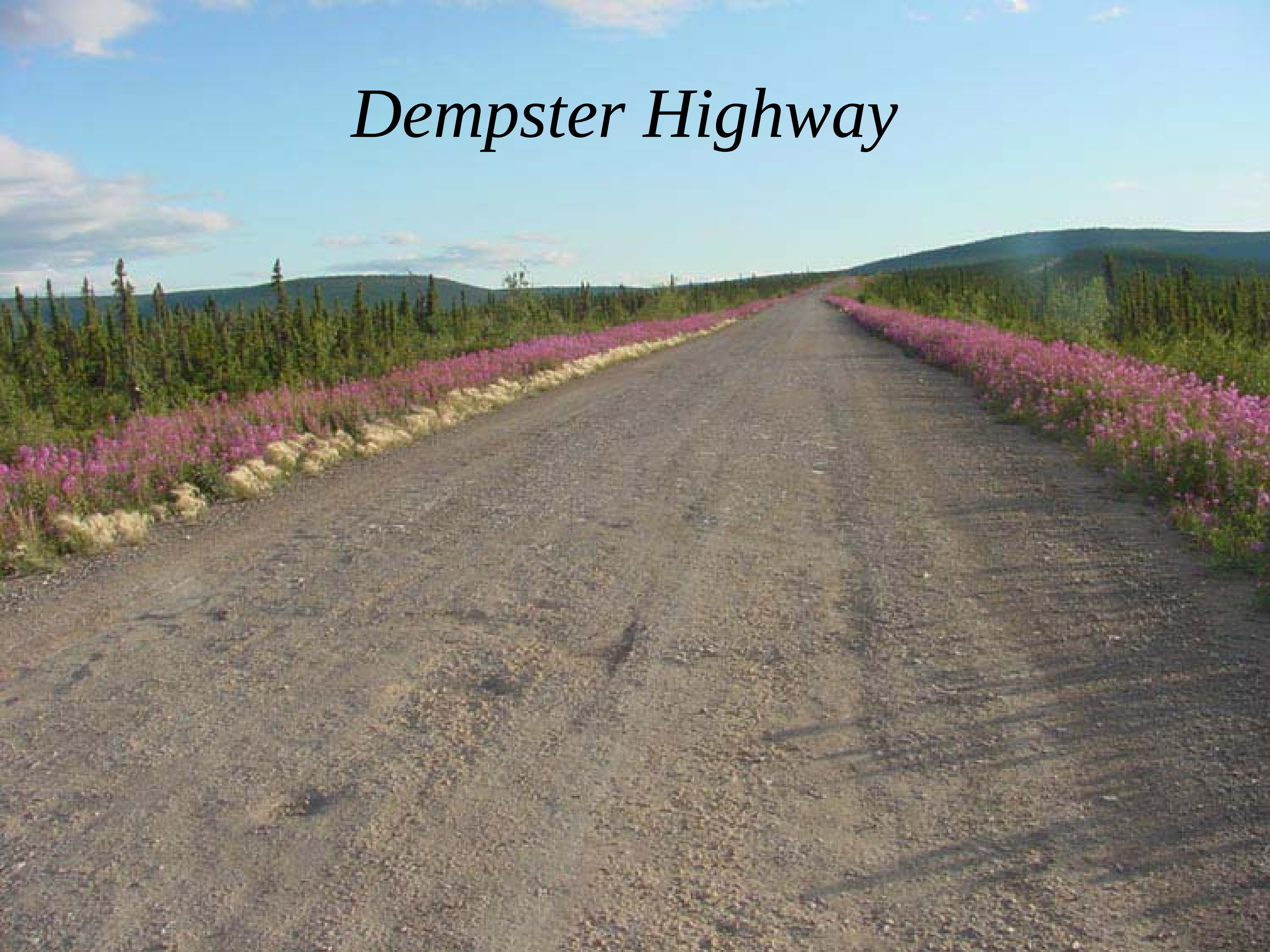
(Based on Vincent 1989)



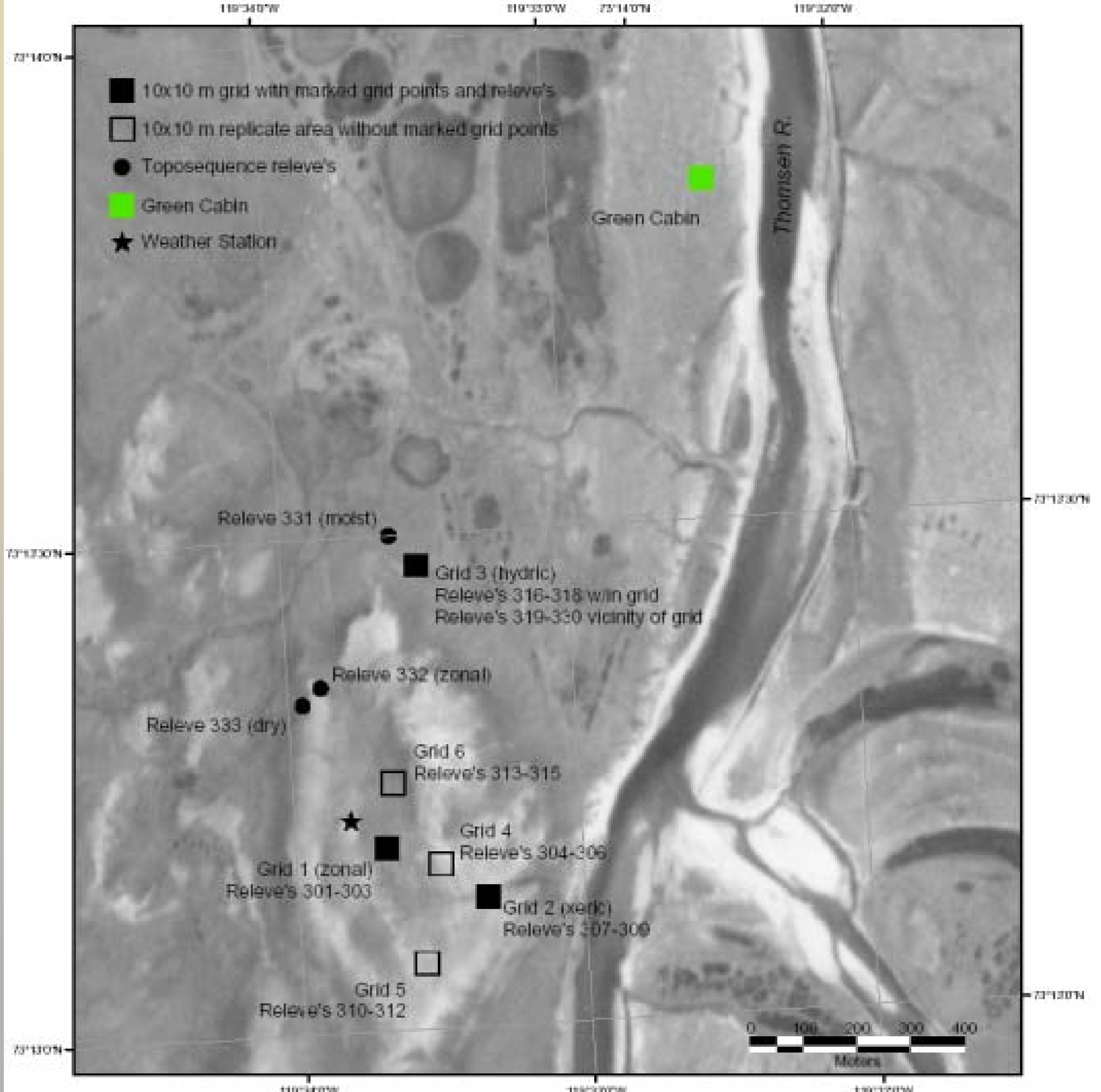
The landscape

Oxytropis arctica

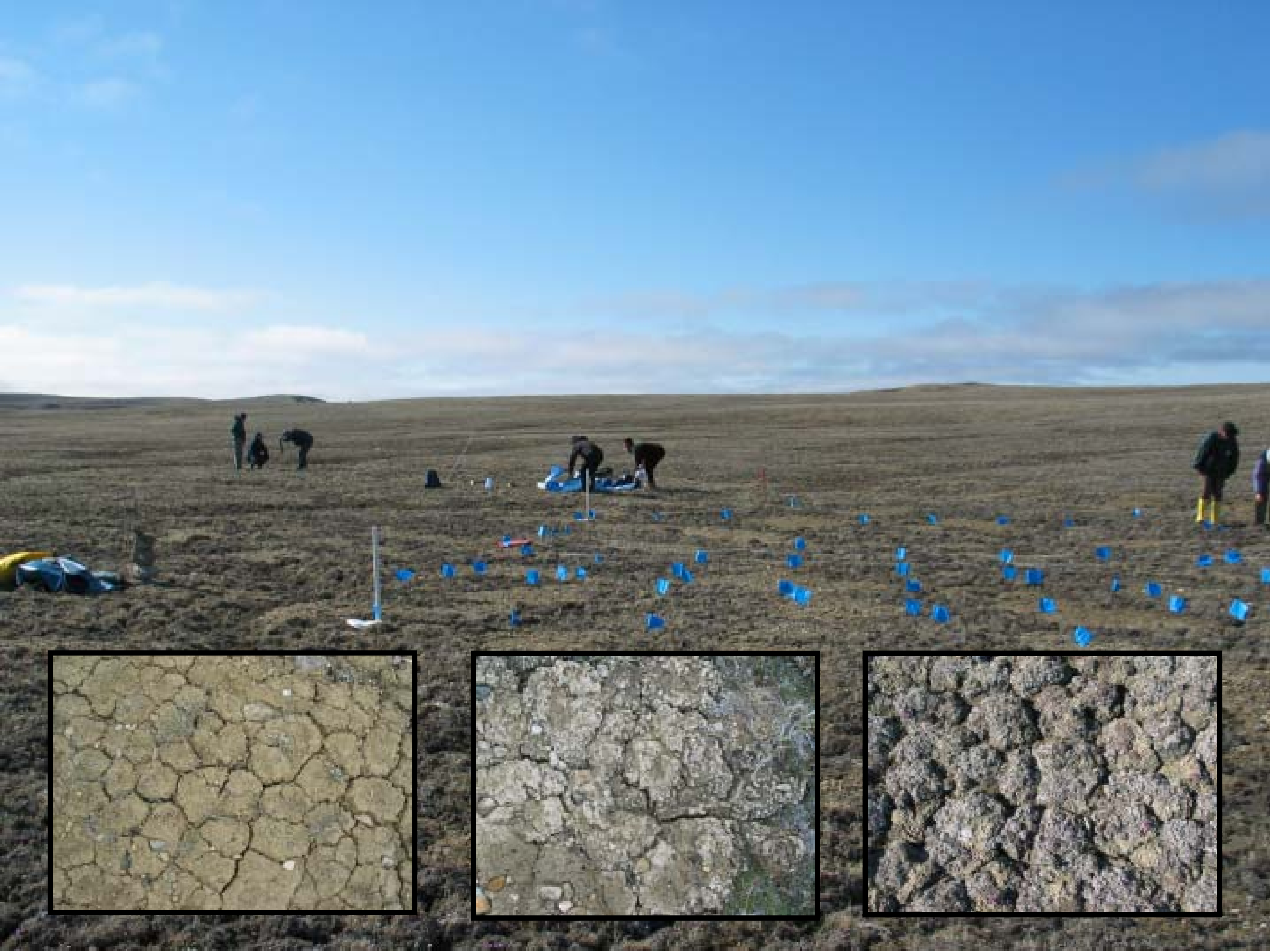
Oxytropis arctobia


Dempster Highway

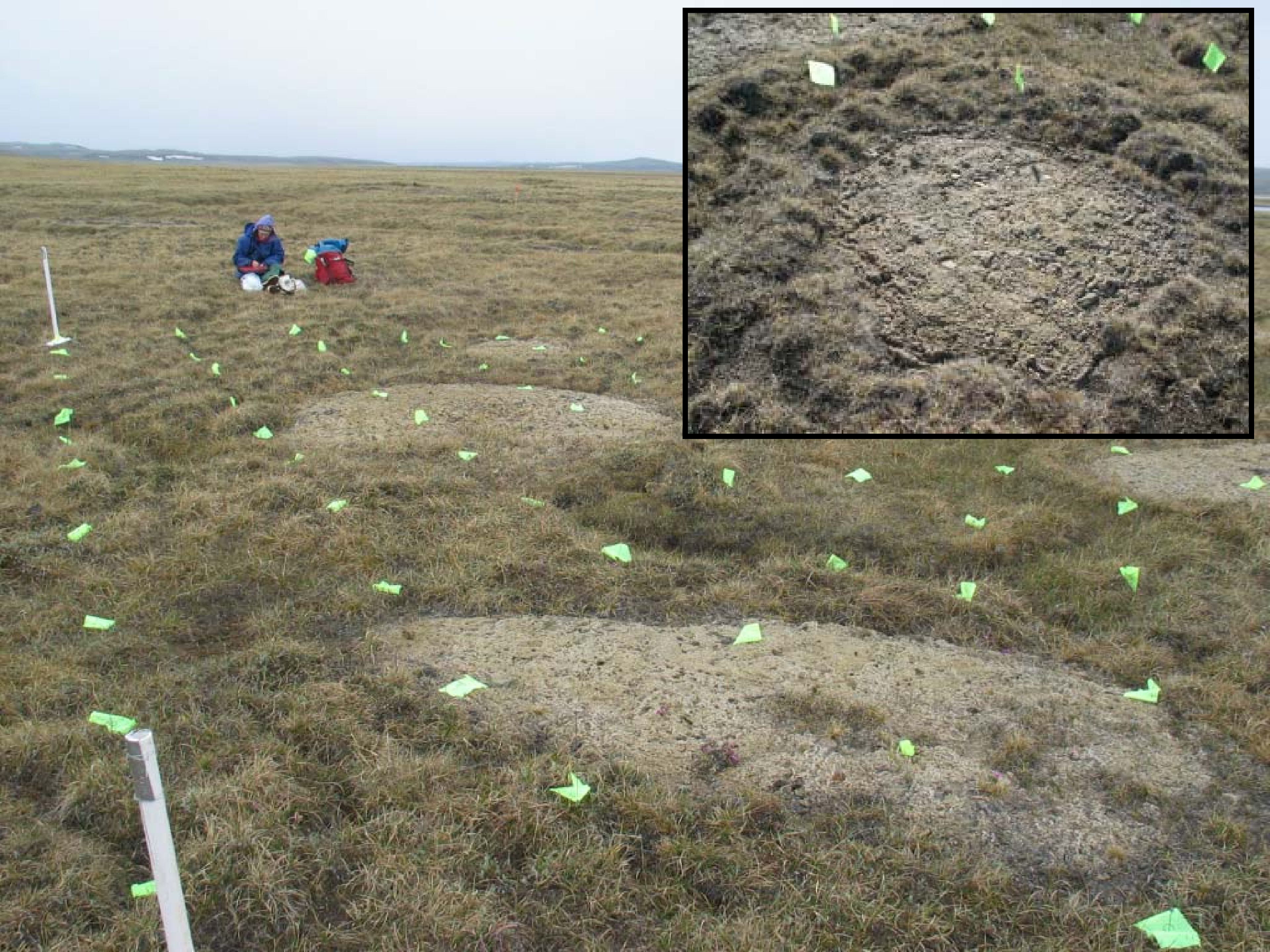
Study sites



10x10 m grid with marked grid points and releve's
10x10 m replicate area without marked grid points
Toposequence releve's
Green Cabin
Weather Station
Green Cabin
Thomsen R.
Releve 331 (moist)
Grid 3 (hydric)
Releve's 316-318 w/in grid
Releve's 319-330 vicinity of grid
Releve 332 (zonal)
Releve 333 (dry)
Grid 6
Releve's 313-315
Grid 4
Releve's 304-306
Grid 1 (zonal)
Releve's 301-303
Grid 2 (xeric)
Releve's 307-309
Grid 5
Releve's 310-312
0 100 200 300 400
Meters

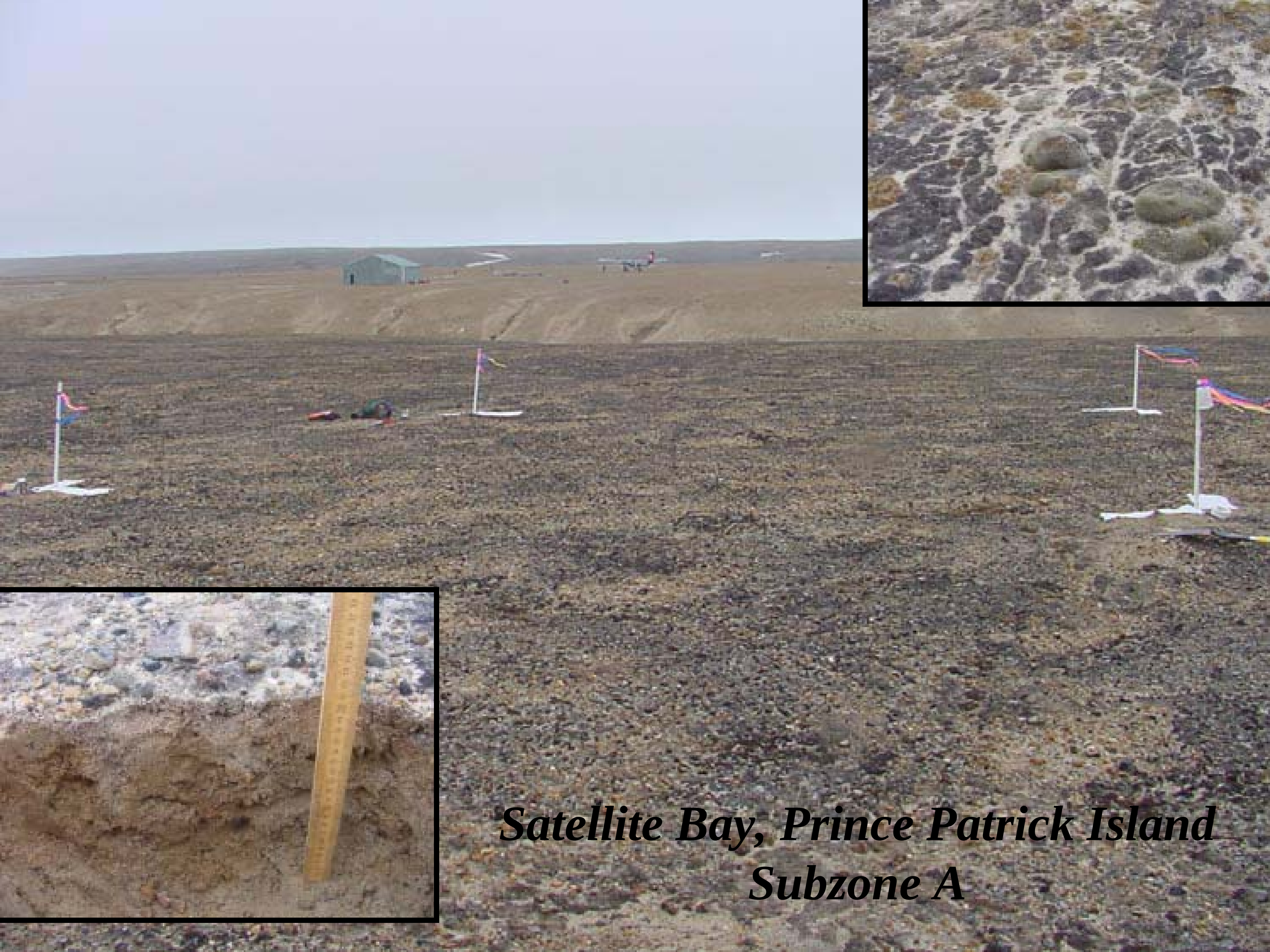


Cryptogamic crust on dry frost boil



Marl with interior lining of algae and fungal hyphae


Mould Bay, Prince Patrick Island,
Subzone B


Satellite Bay, Prince Patrick Island
Subzone A

Key publications

Peterson, R. A., and W. B. Krantz. 2002, in press. A mechanism for differential frost heave and its implications for patterned ground formation. *Journal of Glacialogy*.

Peterson, R. A., D. A. Walker, V. R. Romanovsky, J. A. Knudson, M. K. Raynolds, and W. B. Krantz. 2003, in press. A differential frost heave model: cryoturbation-vegetation interactions. *in Proceedings 8th International Conference on Permafrost*, Zurich, Switzerland, July 21-25, 2003.

Ping, C.L., G.J. Michaelson, J.M. Kimble, and D.A. Walker. 2002. Morphogenesis of soils associated with frost boils in Arctic Alaska. *Eos Transactions.* AGU Fall Meeting Supplement, Abstract # F259.

Walker, D. A., H. E. Epstein, W. A. Gould, J. A. Knudson, W. B. Krantz, R. A. Peterson, C. L. Ping, M. A. Raynolds, and V. E. Romanovsky. 2003 in press. Biocomplexity of frost-boil ecosystems: a conceptual model of morphology in relation to vegetation along a bioclimate gradient. *Permafrost and Periglacial Processes*.

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Photo courtesy of Martha Raynolds




Inuvik