Interactions of multiple factors for patterned-ground features across the Arctic bioclimate gradient

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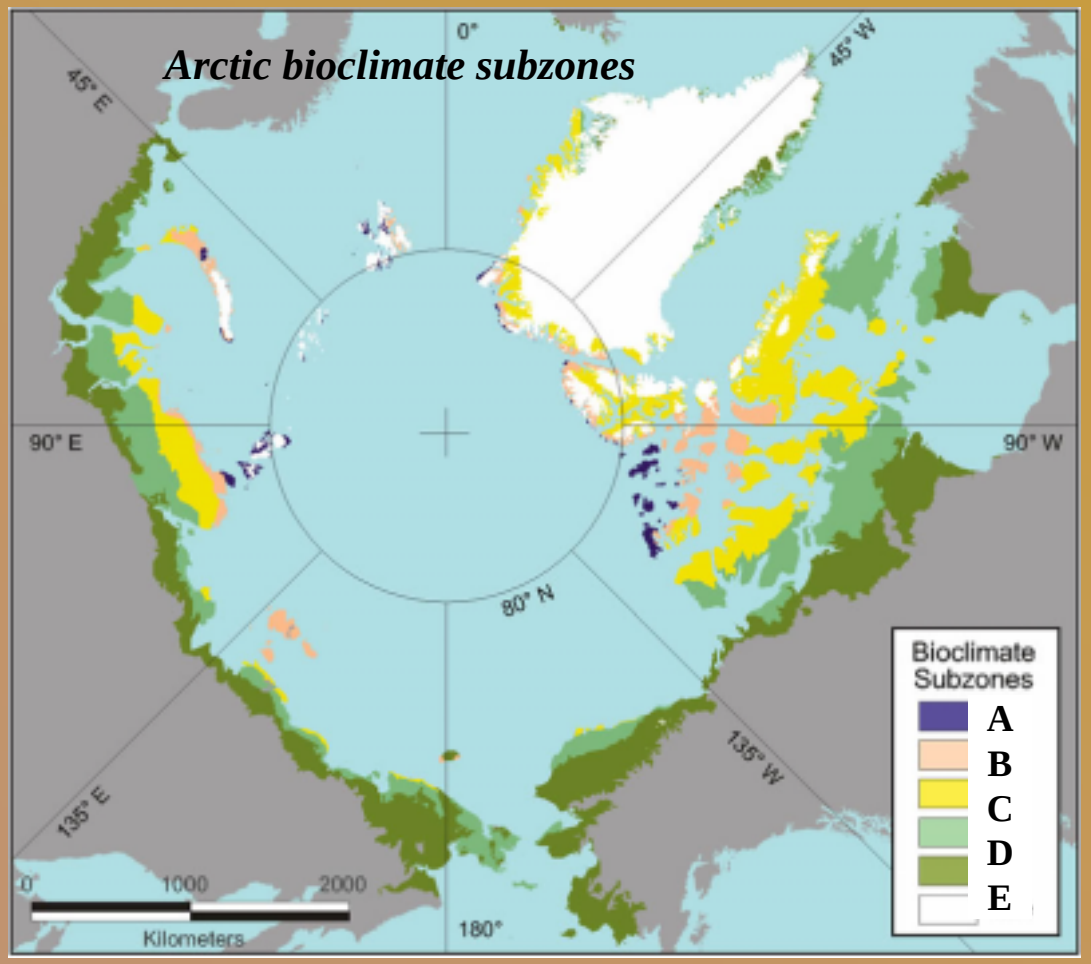
Frost-boil ecosystems: central goal

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 Arctic ecosystem responses to changing climate and land use.

Biocomplexity Grid at Green Cabin, Banks Island, Canada, 2003

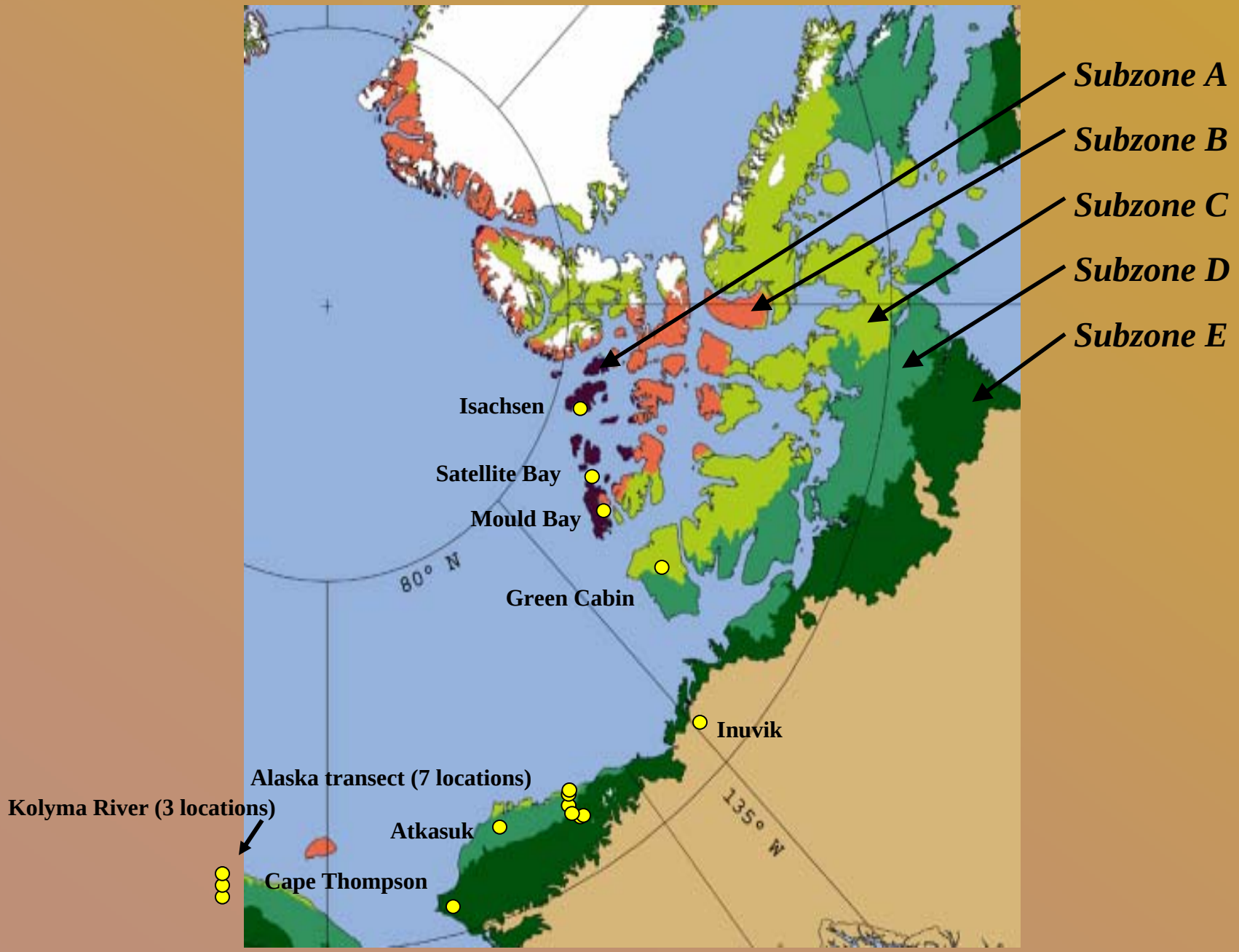
Examination of frost heave features across the Arctic bioclimate gradient using the five subzones of the Circumpolar Arctic Vegetation Map

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*, 2003.

Study sites within the Arctic bioclimate subzones



Project initially focused on “Spotted tundra”

• Washburn (1980) used the term ‘non-sorted circle’ to describe these small 1-3-m diameter barren circles that do not have a ring of stones surrounding them.
• Other terms have included ‘frost medalllion’ (Russian term), ‘mud boil’ (Zoltai and Tarnocai 1981) and ‘frost scar’ (Everett 1966).
• In Russia, landscapes with these features are termed ‘spotted tundra’ (pyatnistye tundry, Dostoyalov and Kudravstev 1967).
• Frost boils’ are thought to be caused by differential frost heave (Peterson and Krantz 2003).

Subzone C, Howe Island, AK

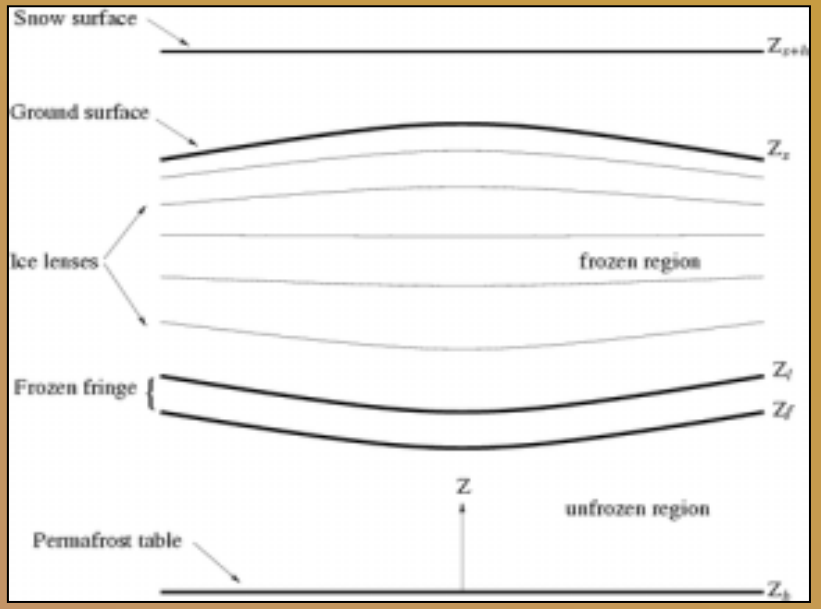
Differential frost heave (DFH) model of frost-boil self-organization (Peterson and Krantz 2003)

- *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 become 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) and 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.

Other forms caused by differential frost heave

- ‘Sorted circles’ (Washburn 1980).
- ‘Earth hummocks’ (Zoltai and Tarnocai 1981).
- There appears to be no single term that can be used to refer to these features collectively.
- We used ‘frost boil’ to refer generically to this variety of forms caused by differential heave.

Sorted Circles at Mould Bay, Canada, Elevation Belt A.

Earth hummock, Inuvik, NWT, Candada,, Northern Boreal Forest

Contraction Cracking

Mould Bay, Prince Patrick Island, Elevation, Belt A.

Contraction cracks in a drained lake basin, Prudhoe Bay, Alaska, Subzone D.

Green Cabin, Banks Island, Bioclimate Subzone C.

Howe Island, northern Alaska, southern Bioclimate Subzone C.

- Contraction cracking at small scales is evident on most fine-grained soils in the High Arctic (Subzones A, B, C).
- Washburn (1980) and Tricart (1967) attributed most fine-scale (<1-m diameter polygons) to desiccation cracking.
- Washburn (1980) did attribute some intermediate-scale (1-10 m diameter) polygons to *seasonal frost cracking*, which occurs in the active layer.

Desiccation cracking

Mould Bay, Desiccation cracks.

Desiccation cracks. Dinosaur Provincial Park, Alberta.

Evidence for seasonal frost cracking at fine scales

- Deeper cracking than desiccation cracks.
- Cracking occurs in sands.
- Ubiquitous features on most High Arctic surfaces with fine-grained soils.
- Should be more common in other dry non-arctic areas.
- Experiments and models are needed to determine conditions for small-scale thermal cracking.

Thermal contraction cracking?

Green Cabin, hummocks.

Green Cabin, hummock removed from soil.

Hummocks

Green Cabin, Subzone C.

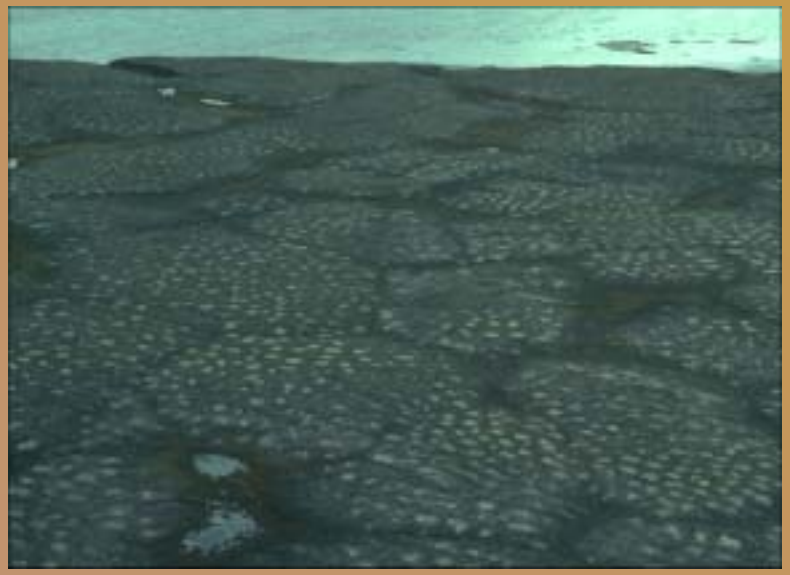
Hummcok cross section, Green Cabin, Subzone C.

- Small 1-30-cm diameter elevated features.
- On hill slopes hummocks are accentuated to about 20 cm heights due to eolian deposition in centers and erosion of troughs between hummocks (Broll and Tarnocai 2002).

Snowbed, Mould Bay, Subzone B..

Contraction cracks, Green Cabin, Subzone C.

Thermal cracking patterns occur at several scales and may be fractal



Ice-wedge polygons and non-sorted circles, Howe Island, Alaska

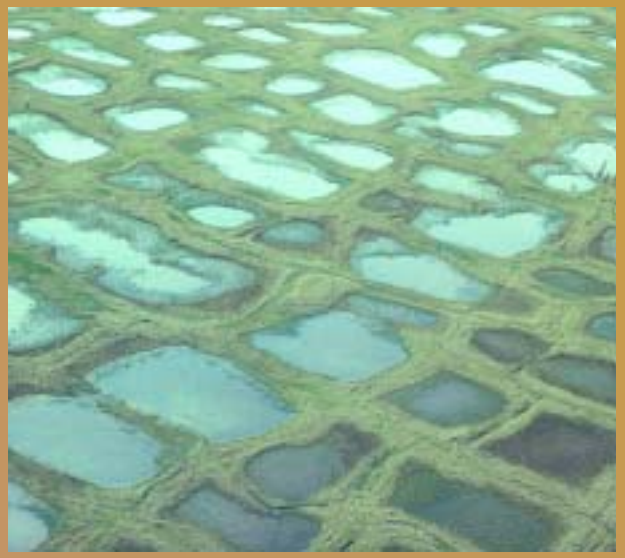
Hummocks, non-sorted circles, and mounds, Howe Island.

Frost cracking within hummocks, Mould Bay.

Frost cracking within Dryas hummock, Green Cabin.

Thermal contraction cracking and ice-wedge polygons

Ice-wedge. Photo: From Washburn 1980



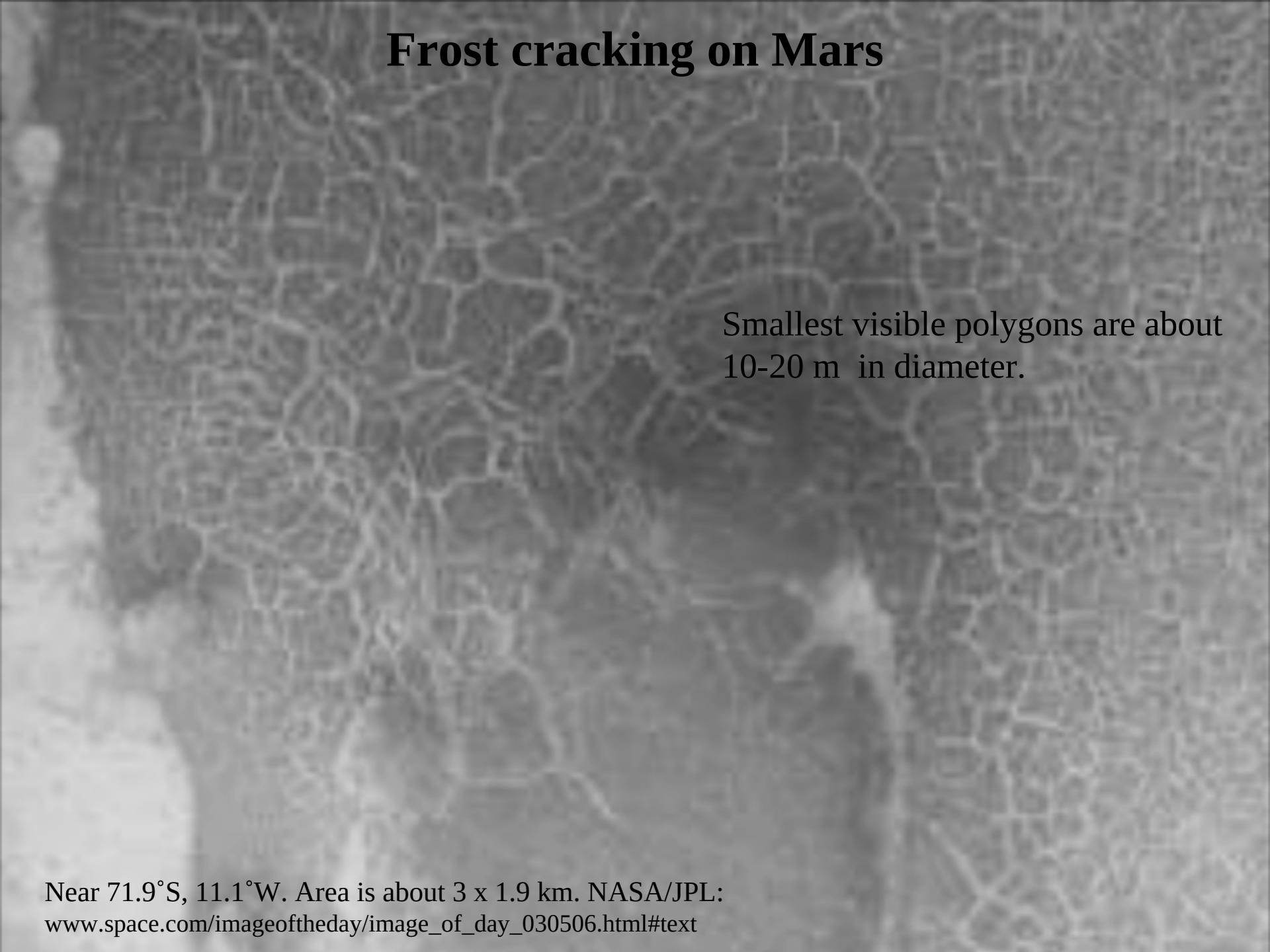
Low-centered polygons, Kuparuk River Delta, Alaska

- Cracking penetrates into the permafrost.
- Much larger polygons, 3-20 m diameter.

Ice-wedge polygons, Prudhoe Bay vicinity, Alaska

Friophorum angustifolium in troughs of flat-centered polygons

Frost cracking on Mars



Smallest visible polygons are about 10-20 m in diameter.

Near 71.9˚S, 11.1˚W. Area is about 3 x 1.9 km. NASA/JPL: www.space.com/imageoftheday/image_of_day_030506.html#text

In the High Arctic contraction cracking interacts with differential frost heave

Howe Island, AK

Photo by Anja Kade

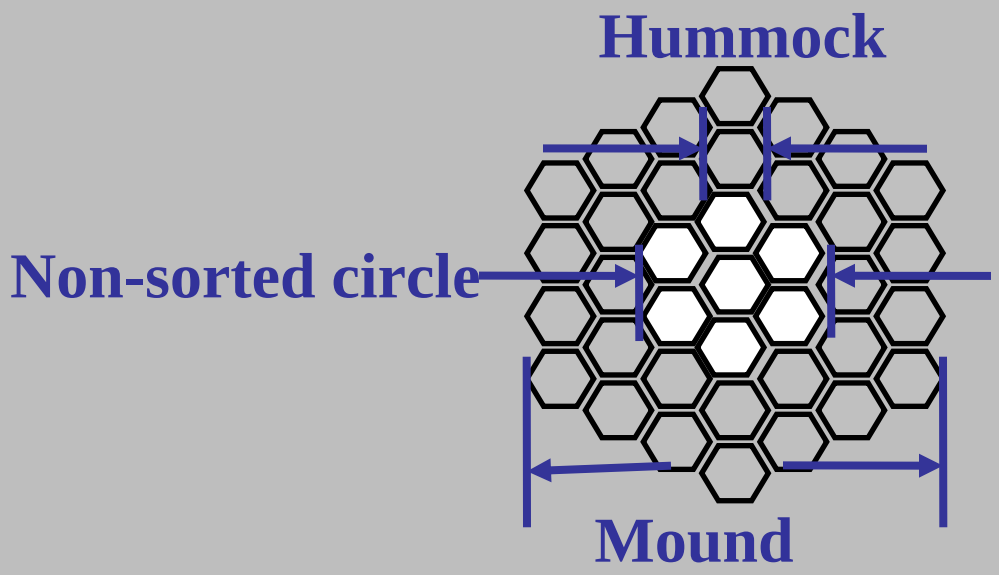
Idealized landscape with hexagonal contraction cracking pattern

• *Small scale polygons (1-50 cm diameter) caused by combination of desiccation and thermal contraction.*

Idealized landscape with cracking pattern that has been modified by differential frost heave

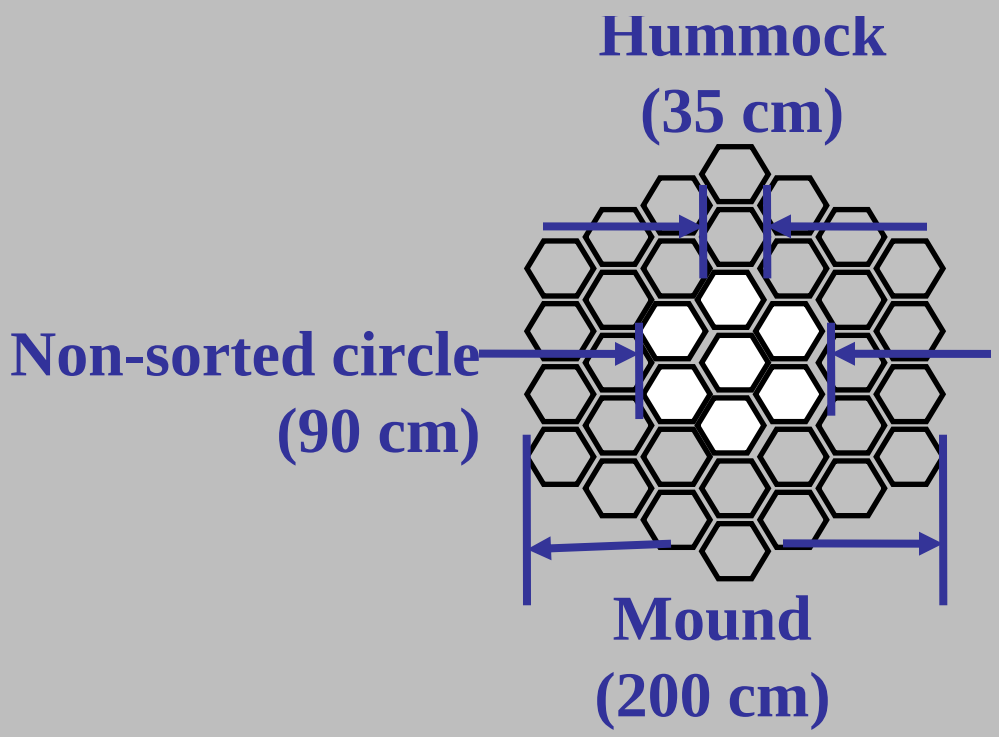
- *Differential frost heave aggregates hummocks into mounds.*
- *Cracks between mounds become favored sites for vegetation accumulation, further enhancing DFH.*
- *Central portion of mounds have non-sorted circles.*

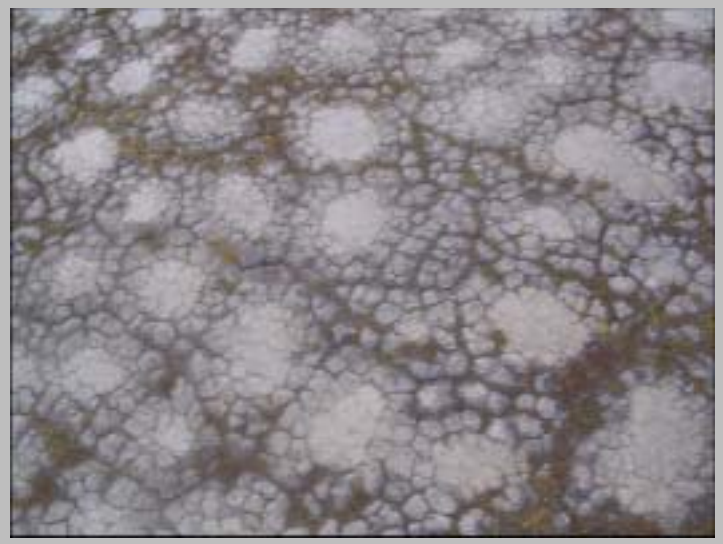
Components of landscape modified by both cracking and differential heave



- *Differential frost heave aggregates hummocks into mounds.*
- *Cracks between mounds become favored sites for vegetation accumulation, further enhancing DFH.*
- *Central portion of mounds have non-sorted circles where heave is maximum.*

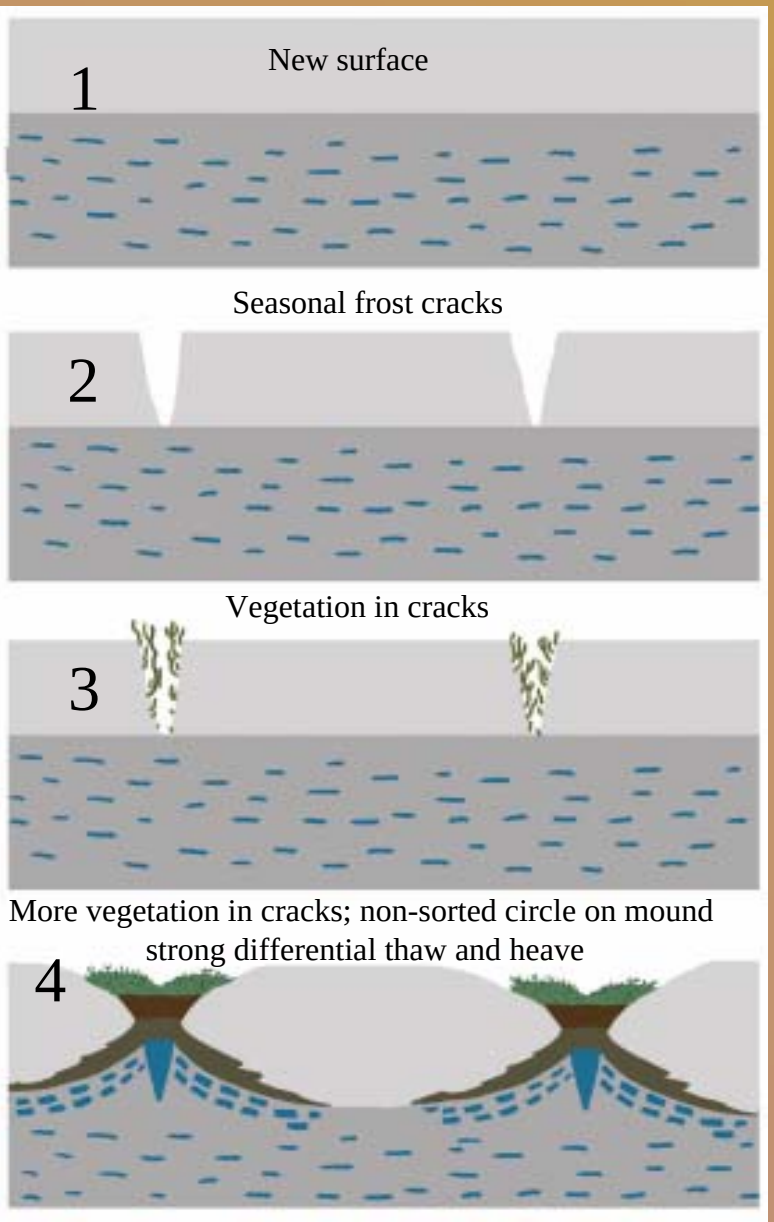
Approximate dimensions of hummock, non-sorted circle, and mounds at Howe Island

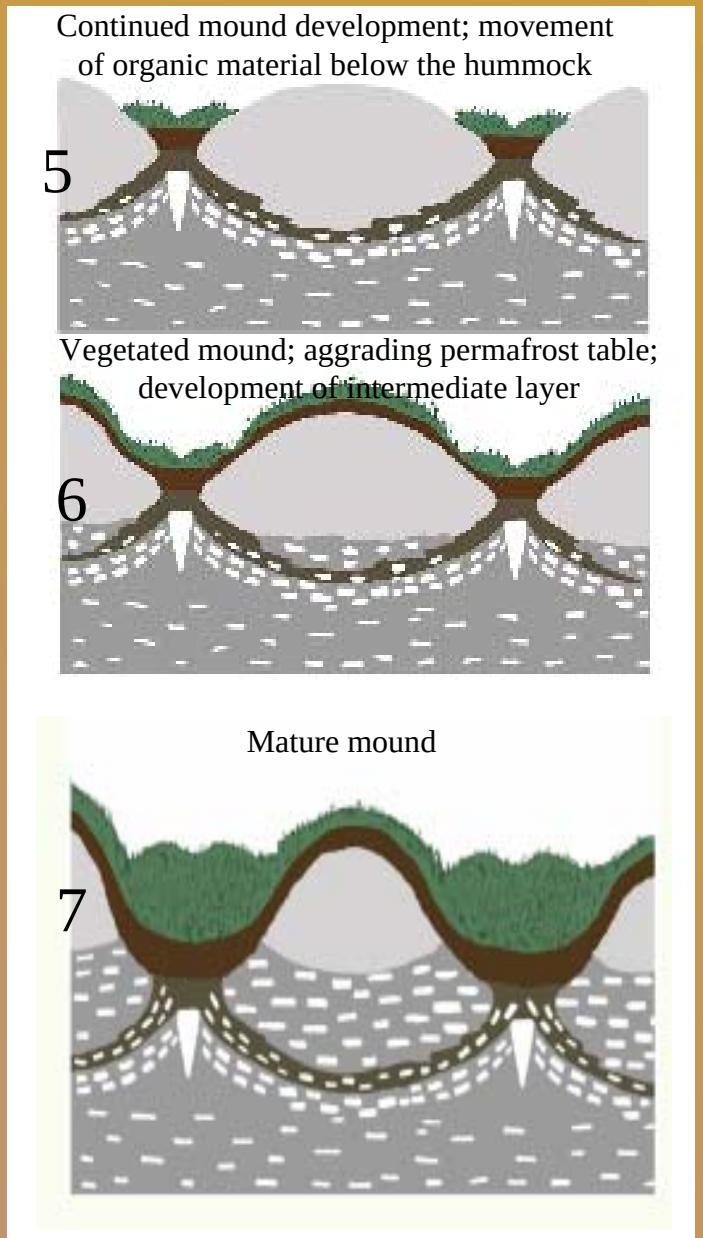




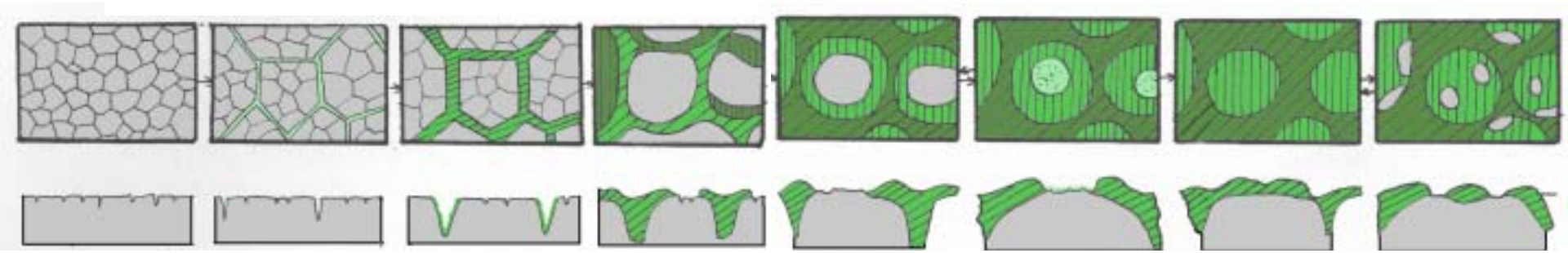
Mounds across the bioclimate gradient

Stages of mound formation: Yuri Shur (2003)





Role of vegetation succession on hummocks, mounds, and non-sorted circles



• **Subzone A:** Contraction cracking and hummock formation. Vegetation (mostly lichens and mosses in cracks.

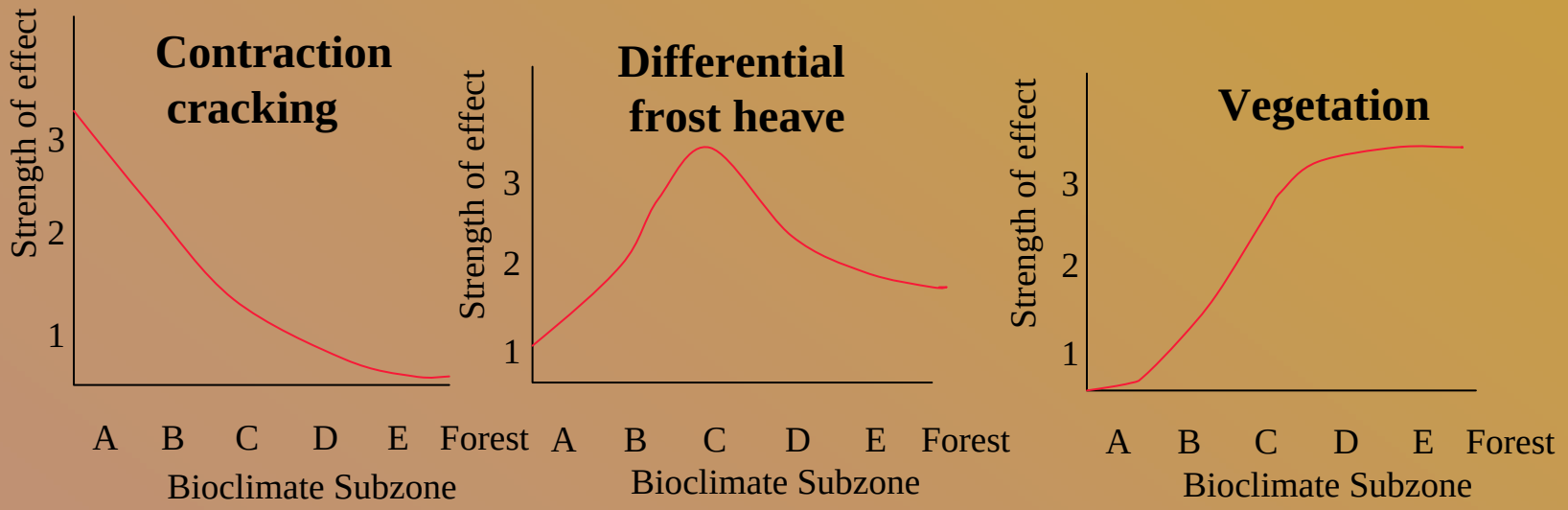
• **Subzone B:** Differential heave causes aggradation of hummocks and initiates mound pattern. Vegetation favors deeper troughs between mounds.

• **Subzone C-D:** Strong contrast between mounds and troughs, Strong differential frost heave. Development of non-sorted circles. Colonization of centers of mounds and non-sorted circles in Subzone D.

• **Subzone E:** Complete cover of vegetation on mounds.

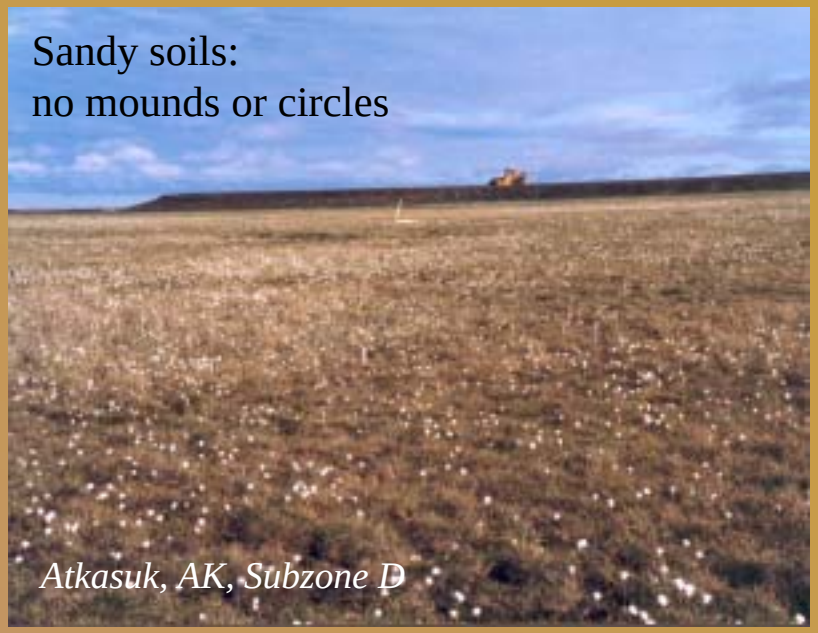
Figure: Modified from Chernov and Matveyeva 1997

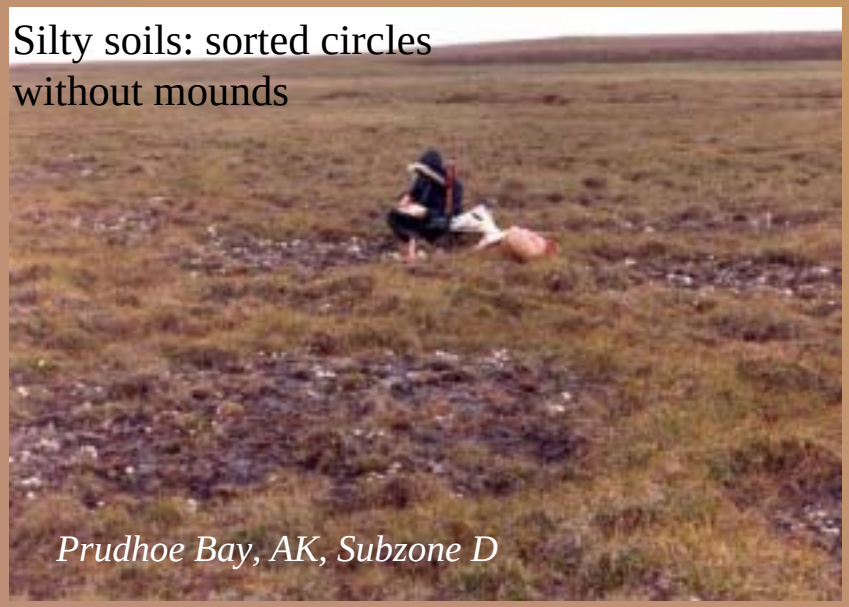
Strength of influence of cracking, differential heave and vegetation succession on small patterned ground forms along the arctic climate gradient



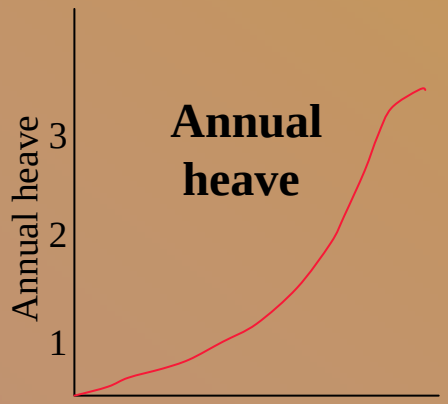
- **Contraction cracks** are most strongly developed in the extreme High Arctic (subzones A and B).
- **Differential frost heave** affects pattern most strongly in the Middle Arctic areas (subzones C and D) where barren mounds and non-sorted circles are mixed with well-developed inter-mound vegetation.
- **Vegetation** has strongest effect for stabilizing heave effects in the Low Arctic (Subzones D and E) where it completely masks contraction cracks and non-sorted circles.

Role of soil texture

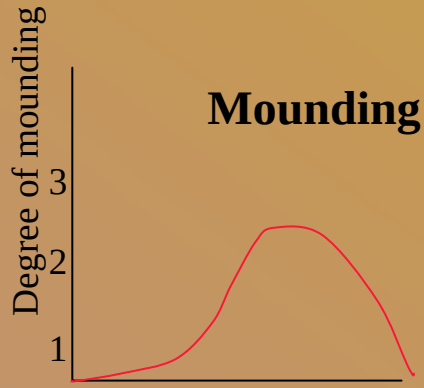




Effects of soil texture on annual heave, mounding, and sorting



Percent silt

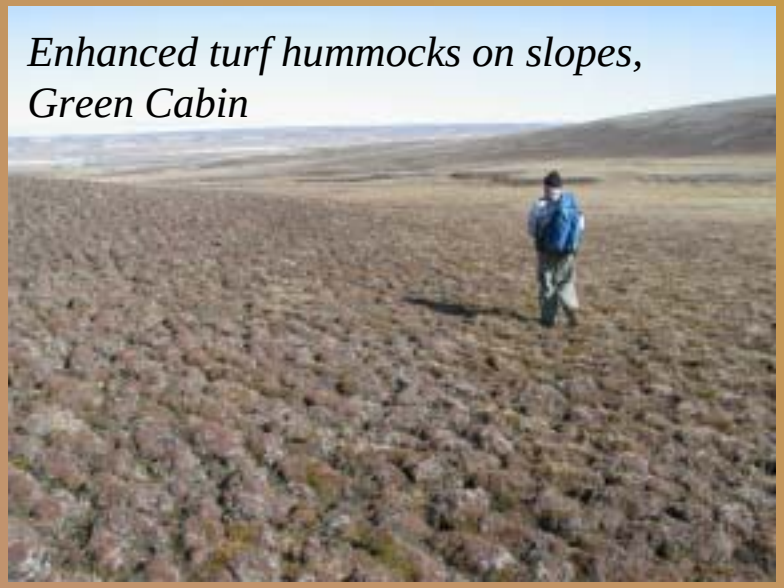


Percent clay

Percent rocks

- **Silts**: lots of annual heave (up to 20 cm in northern Alaska), but little mounding.
- **Clays**: mounds. Heave is on a different time scale and may be greater than in silts over the long term.
- **Pure sands:** No heave. No circles or mounds.
- **Course-textured soils:** Sorted circles and polygons, heaving occurs due to the finer grain sizes.

- Clayey soils – little annual heave, soils apparently do not relax with thaw and maintain mound shape in the summer. Very clayey soils do not develop differential heave.



Enhanced turf hummocks on slopes, Green Cabin

Complexities caused by slope and soil moisture

- Talk has focused on zonal situations (flat to gentle slopes with mesic conditions).
- Examples of effects of non-zonal slope and site moisture:
  - Large hummocks on slopes.
  - Sorted and non-sorted stripes on slopes (Kessler and Werner 2003). Also sorted steps and others (Washburn 1980).
  - Very large non-sorted circles in wet sites.

Non-sorted stripes, Green Cabin

Large non-sorted circles in wet soils, Green Cabin

Problems with ‘frost-boil’ terminology

- Active frost churning (‘boiling’) is often absent from the central portion of these features.
- No single term applies to features across the bioclimate gradient that appear to have a similar genesis related to differential frost heave (non-sorted circles, sorted circles, earth hummocks).
- ‘Frost boils’ appear to be formed by several interacting mechanisms including but not limited to differential frost heave, frost cracking, mass displacement, and sorting.

Washburn (1980) revisited

The following points need to be reevaluated:

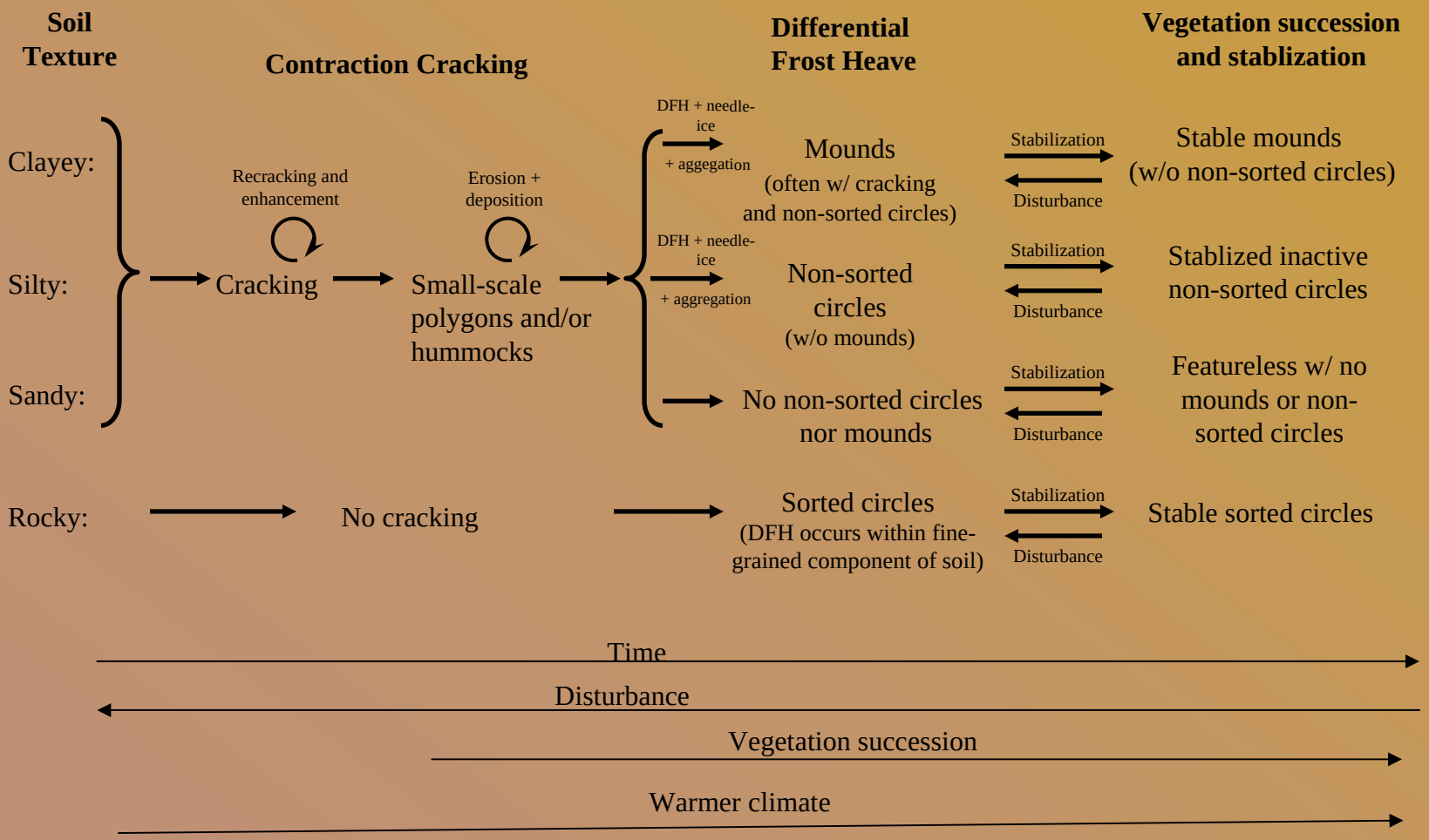
1. The scale and abundance of polygonal features caused by *seasonal frost cracking*.
2. Clarification of terminology related to features caused by seasonal frost cracking and differential frost heave. Our suggestions:

Hummocks: Small scale raised features on the order of 10-50 cm diameter that appear to be caused by enchancement of polygonal features caused by seasonal frost cracking and/or desiccation cracking.

Mounds: Larger scale 1-3 m diameter raised features that appear to be caused by differential frost heave.

Non-sorted circles: Barren patches 0.5-3 m diameter related to differential frost heave, often in the center of mounds.

Toward a comprehensive theory for the polygenetic origins of small periglacial surface forms



Note: figure applies to flat moderately drained sites.

Conclusions

- **Frost cracking**, **differential frost heave**, and **vegetation** interact to form a continuum of small peri-glacial surface forms across the Arctic bioclimate gradient.
- **Cracking** is a dominant process in the High Arctic and forms small polygons and hummocks 10-20 cm across. Cracking appears to be caused by thermal contraction within the active layer and may be fractal in nature. Experiments are needed to determine the conditions under which cracking develops.
- **Differential frost heave** aggregates hummocks into larger polygons or mounds 1-2 m across.
- **Vegetation** masks and obliterates the fine scale cracking pattern where vegetation processes are strong, especially in warmer climates. Vegetation also affects soil thermal properties, thickness of the thaw layer, differential frost heave, mound morphology, and formation of the intermediate layer and sequestered carbon in the permafrost.
- **Soil texture** affects the heave and characteristic patterns:
  - Coarse textured soils: sorted circles.
  - Sands: have little or no differential heave or non-sorted circles.
  - Silts: large annual heave; flat non-sorted circles; and mounds are uncommon.
  - Clays: mounded features; little annual heave.
- **Slope and soil moisture** modify the forms that develop on flat mesic sites (e.g., turf hummocks, sorted and non-sorted stripes, large circles in wet areas.