Geophysical Self-Organization as an Indicator of Global Climate Change

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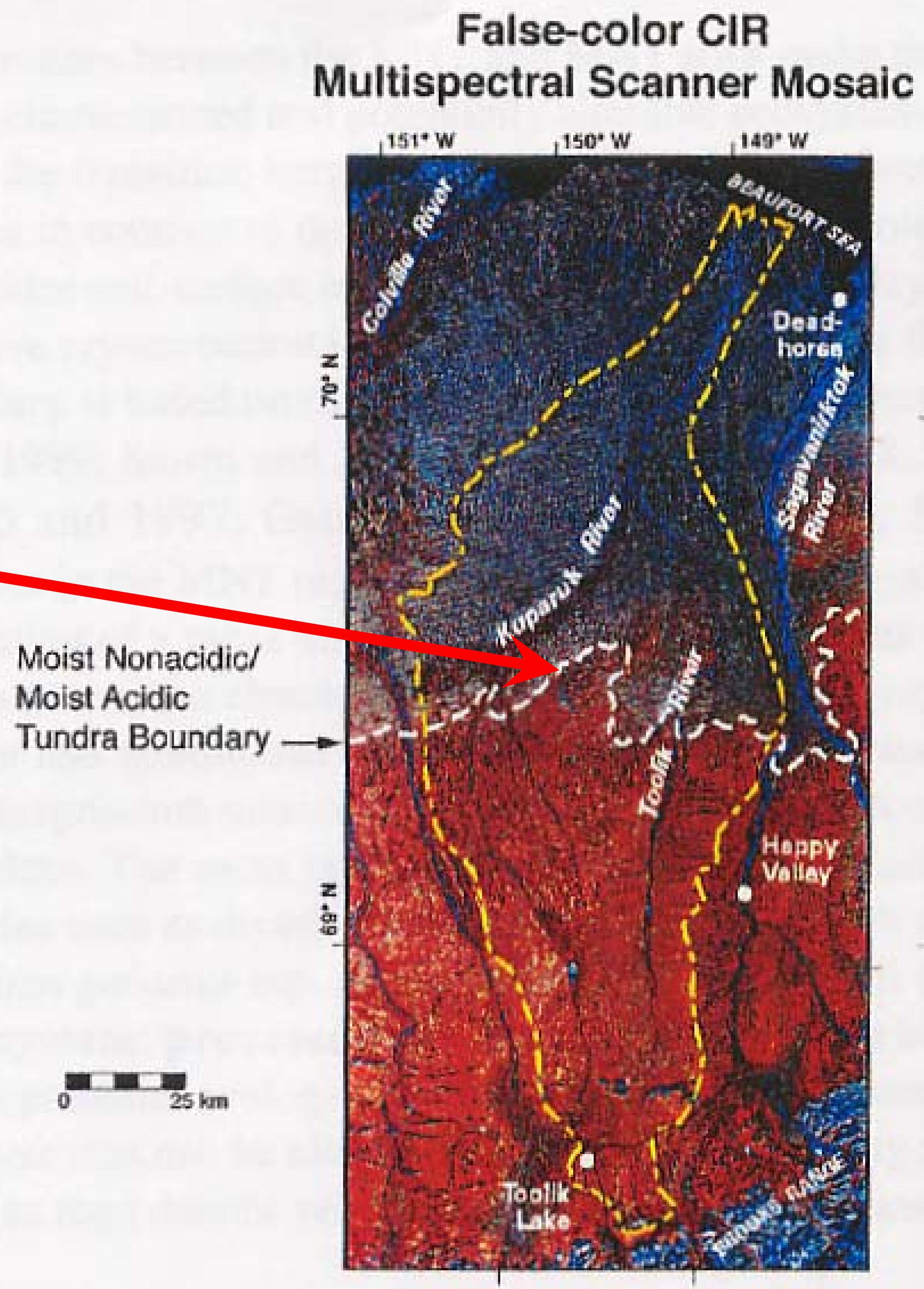
Biocomplexity Field Excursion
June 30 – July 15, 2003

Global Climate-Change Considerations

- Observable on 10 to 100-year time scale
- Not subject to direct anthropogenic disturbances
- Observable via remote sensing

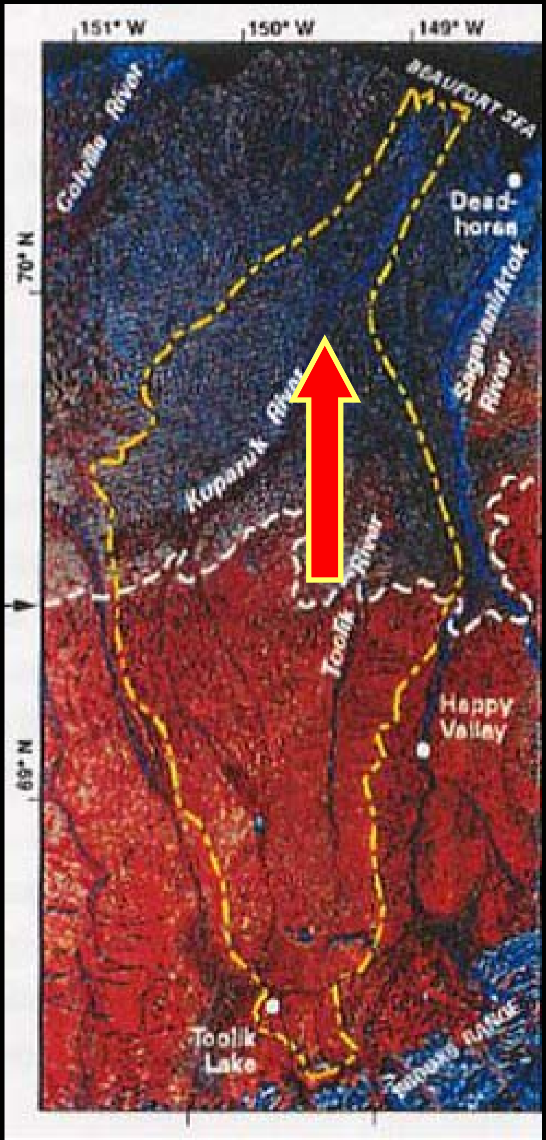
Remote Sensing Shows Sharp Dividing Line in Arctic Tundra



Arctic Frost Boils

Frost Boils as an Indicator of Global Climate Change

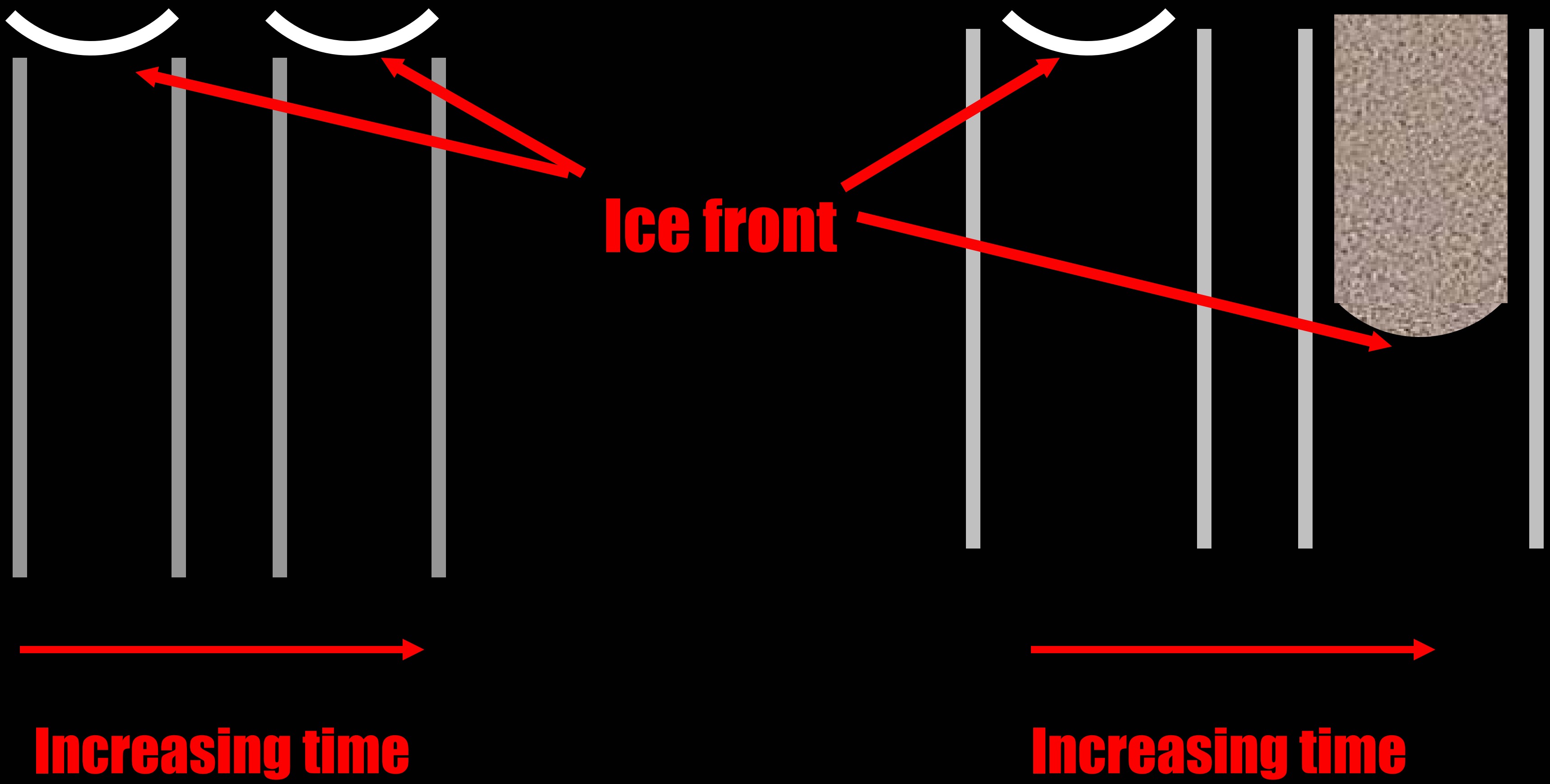
Northward movement of line between acidic & nonacidic tundra indicative of global warming causing reduced frost-boil activity – vegetation changes provide early warning system if they can be related to frost-boil activity



Differential Frost Heave (DFH) Model for Frost-Boil Formation

Model assumes DFH causes ground surface corrugations – lateral extension of ground surface owing to more frost action prevents development of vegetation under crest regions – this causes centers of frost boils to appear barren relative to trough regions – moisture accumulation in troughs relative to crests accentuates differences in the micro-ecosystem created by the frost boils

Effect of Pore Size on Freezing Temperature Depression

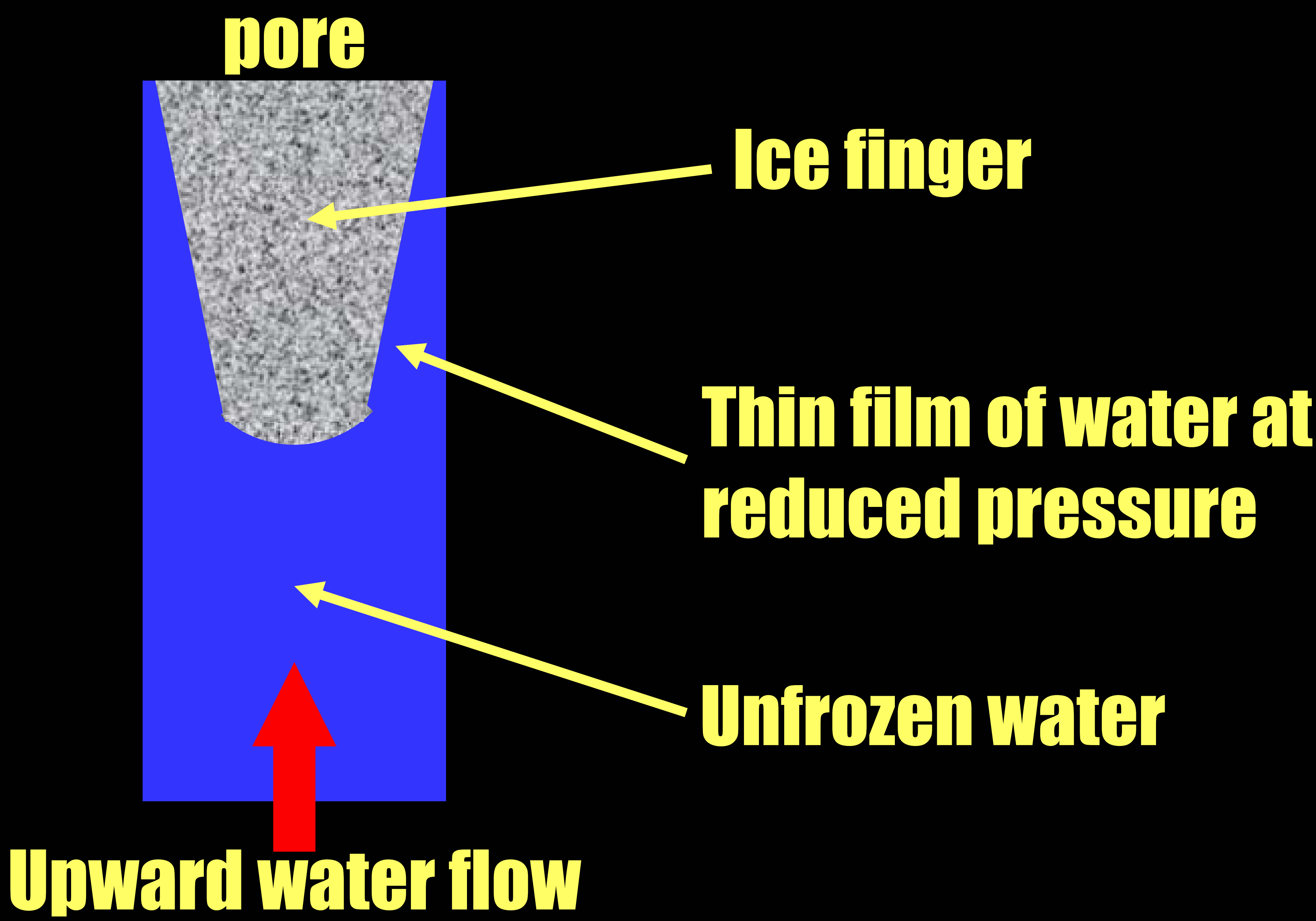


Ice cannot penetrate into smaller pores until temperature is reduced sufficiently – i.e, freezing point depression

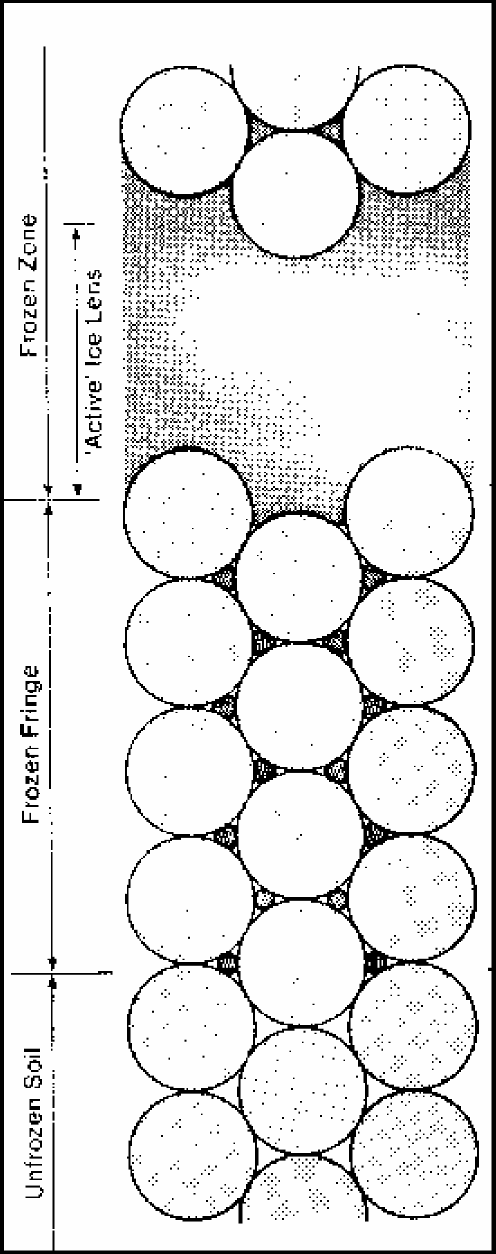
Why Freezing Causes Upward Flow of Water

- Soils are wet by liquid water not ice
- Ice fingers in pores becomes thicker with decreasing temperature
- Pressure in thin film of liquid water between ice and soil decreases
- This ‘cryostatic suction’ draws water up from the underlying water table

Cryostatic Suction in a Pore

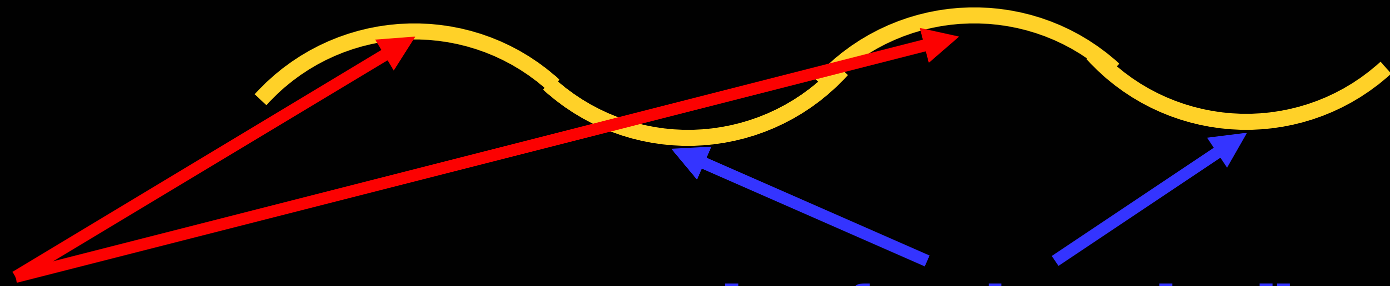


Frost Heave



Occurs due to expansion of freezing water drawn upward by cryostatic suction – ice carries progressively more of soil load until net force compressing soil particles is zero – this permits ice-lens formation between soil grains – ice-lens formation continues until downward penetrating freezing front reduces soil permeability sufficiently to cut off subterranean water upflow – this process then repeats with successive ice lenses becoming thicker owing to the decrease in frost penetration

Differential Frost Heave

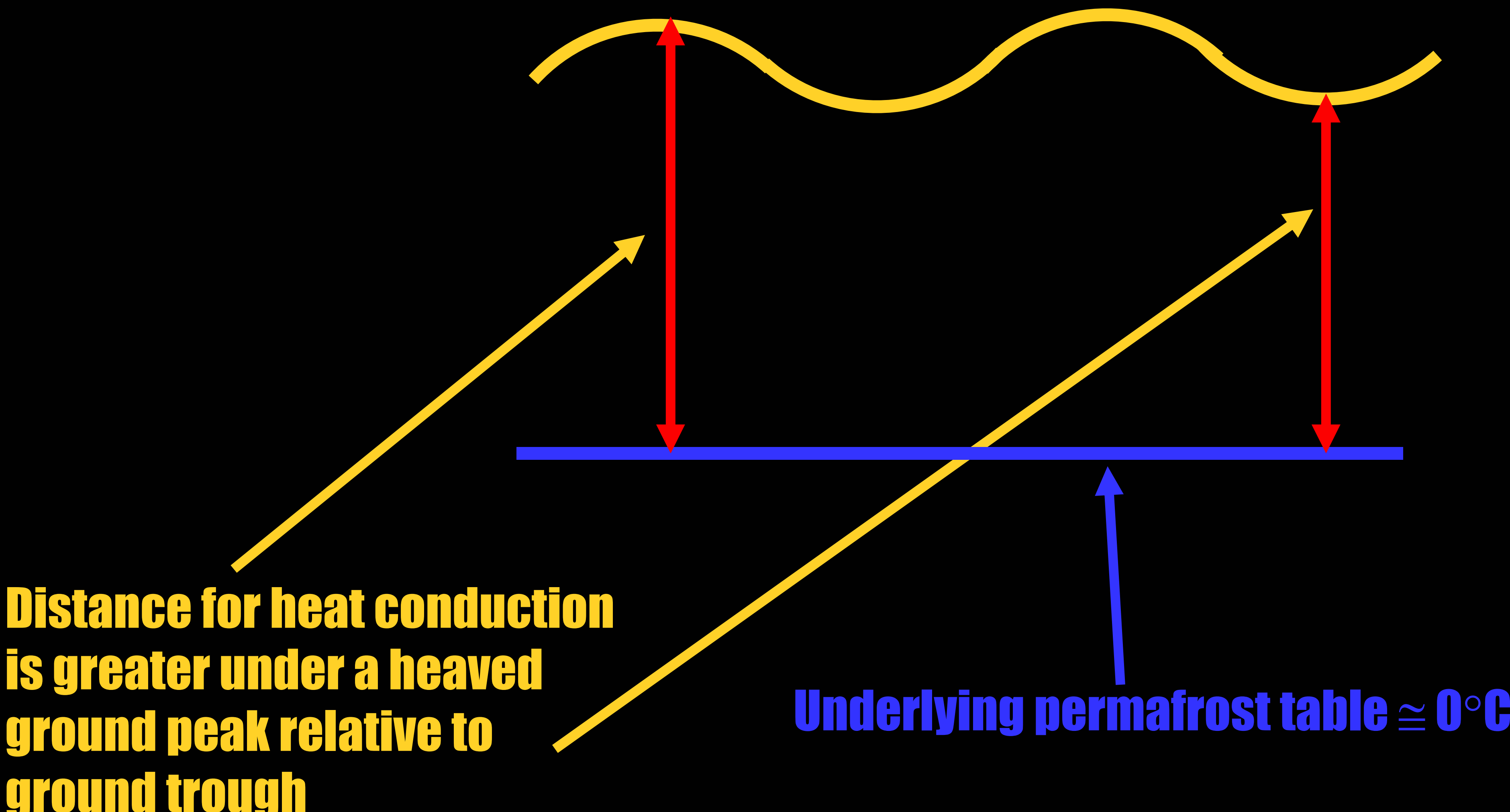


Increased frost heave implies larger heat transfer to the surroundings

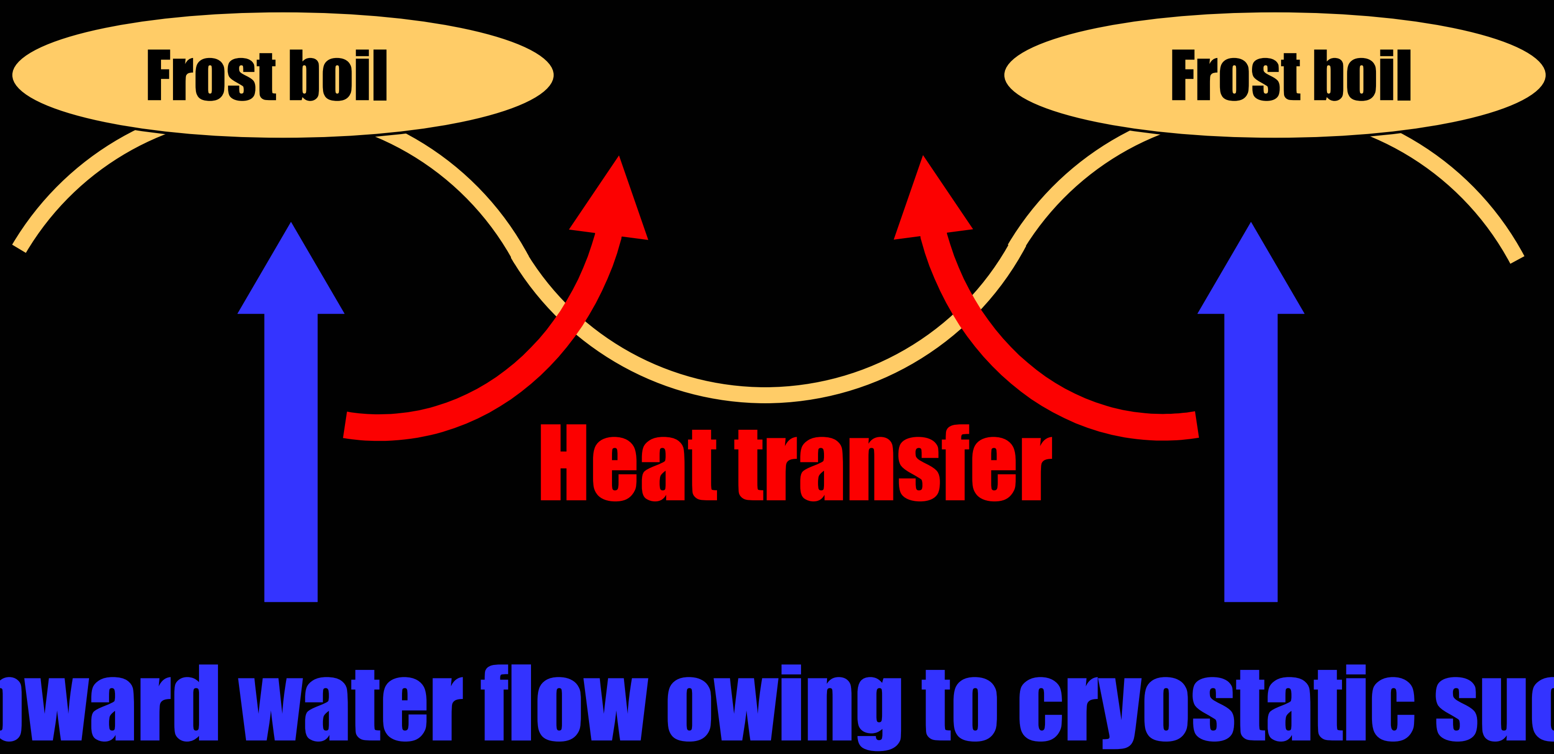
Less frost heave implies reduced heat transfer to the surroundings

Frost boils are manifestation of differential frost heave, i.e., frost heave that varies laterally – for this to occur, there has to be greater capacity to remove latent heat of fusion of ice under regions where frost heave is greater

Paradox Presented by Differential Frost Heave!



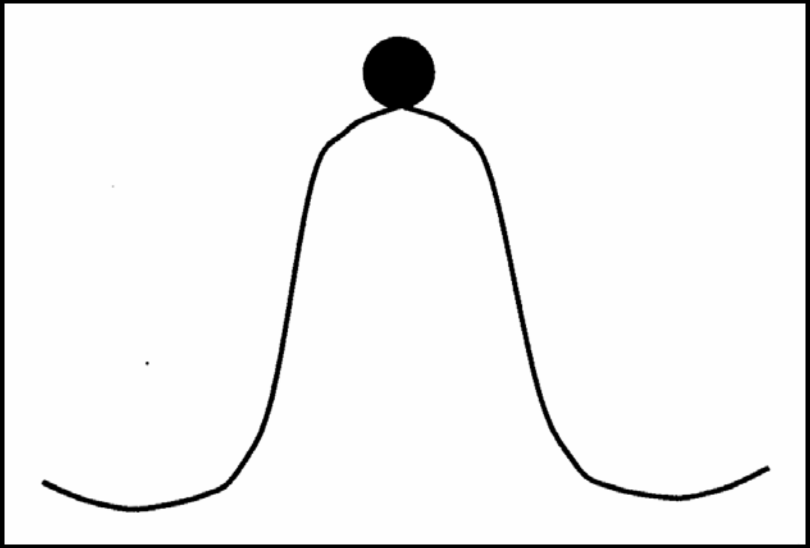
Reason Why Frost Boils Form
(geophysical self-organization)



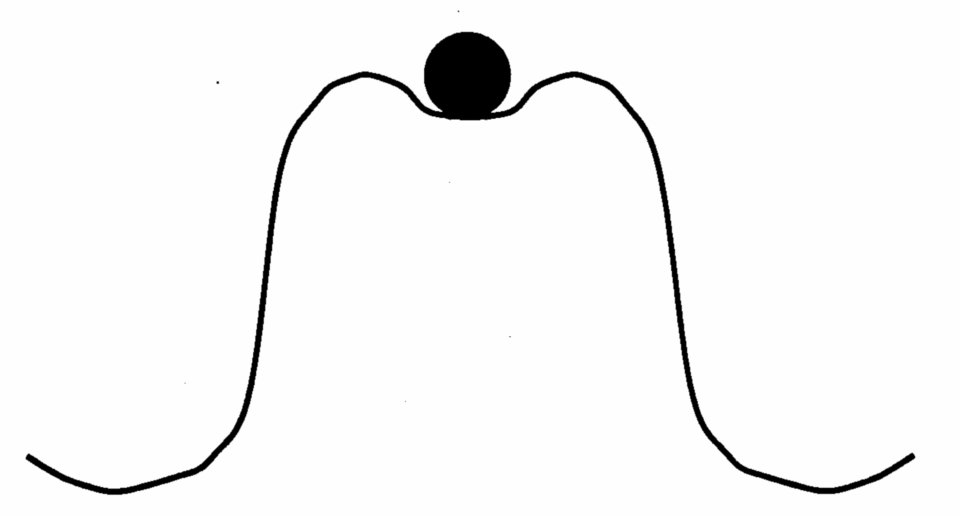
Mathematical Modeling Approach – Stability Analysis

Stability theory approach to differential frost heave (DFH) mathematically asks question "Is there any tendency for the one-dimensional frost-penetration process to evolve into multidimensional frost heave?" – it considers whether small departures from one-dimensional frost penetration are energetically favorable – it can determine conditions required for DFH to occur and how environmental parameters (temperature, ground cover, snow depth, wind speed, etc.) influence its occurrence

Illustration of Stability Analysis

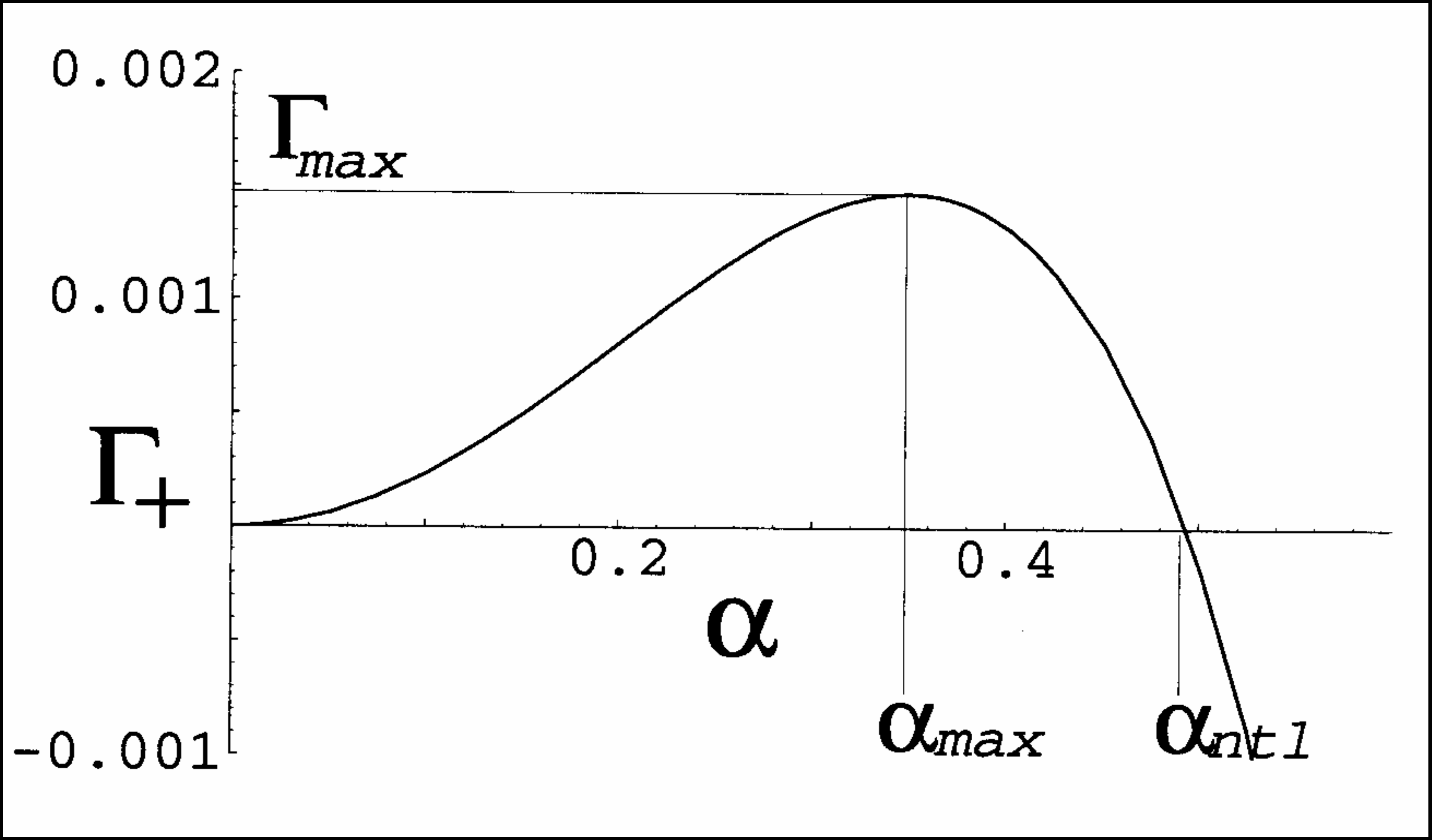


Linear Stability Theory



Nonlinear Stability Theory

Typical Linear Stability Theory Predictions for DFH



Plot of growth coefficient as a function of wave number (reciprocal wavelength) for Chena silt.

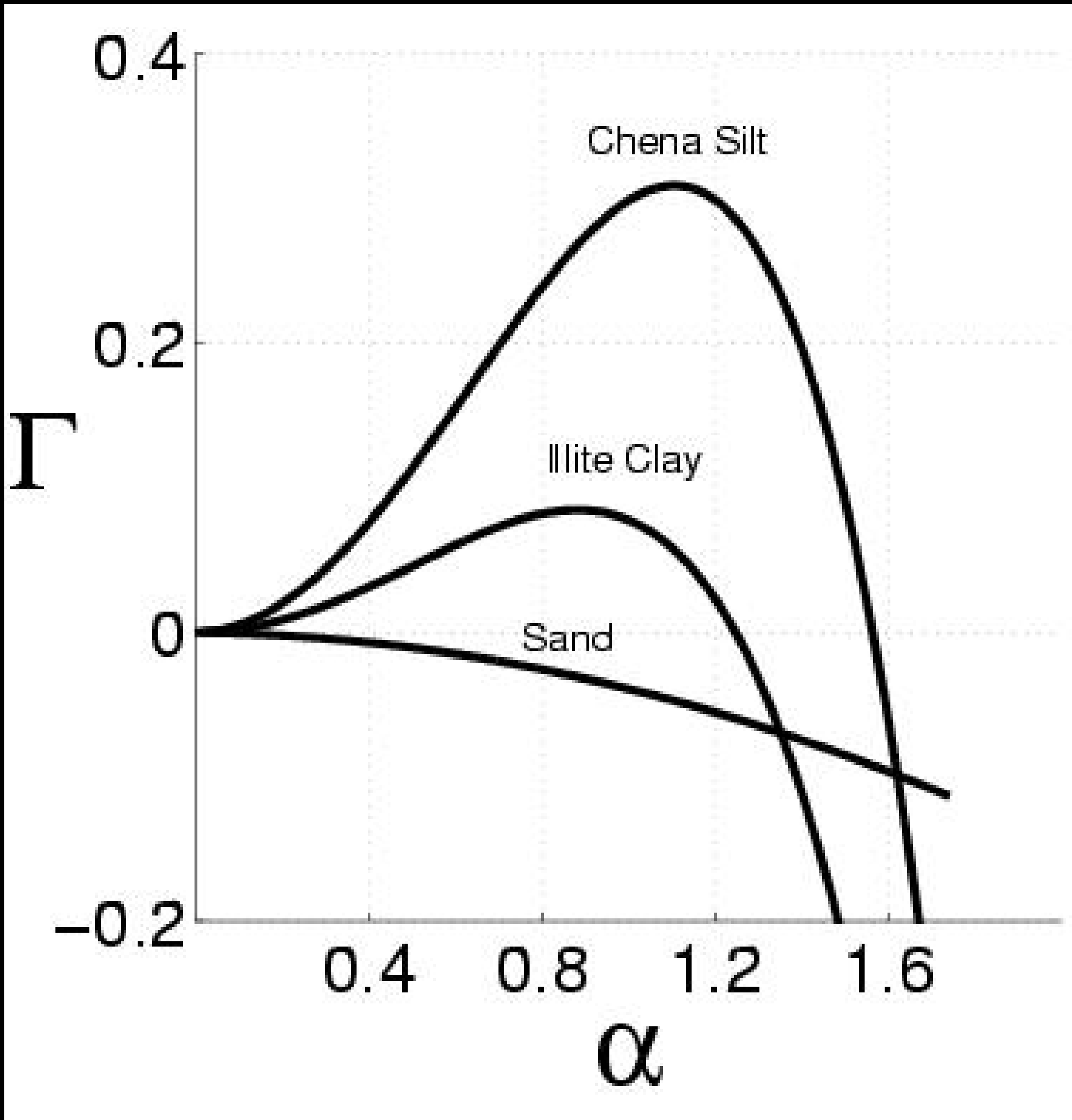
Frost Boils and the Ecosystem

Ecosystem variables that impact frost-boil activity include the following:

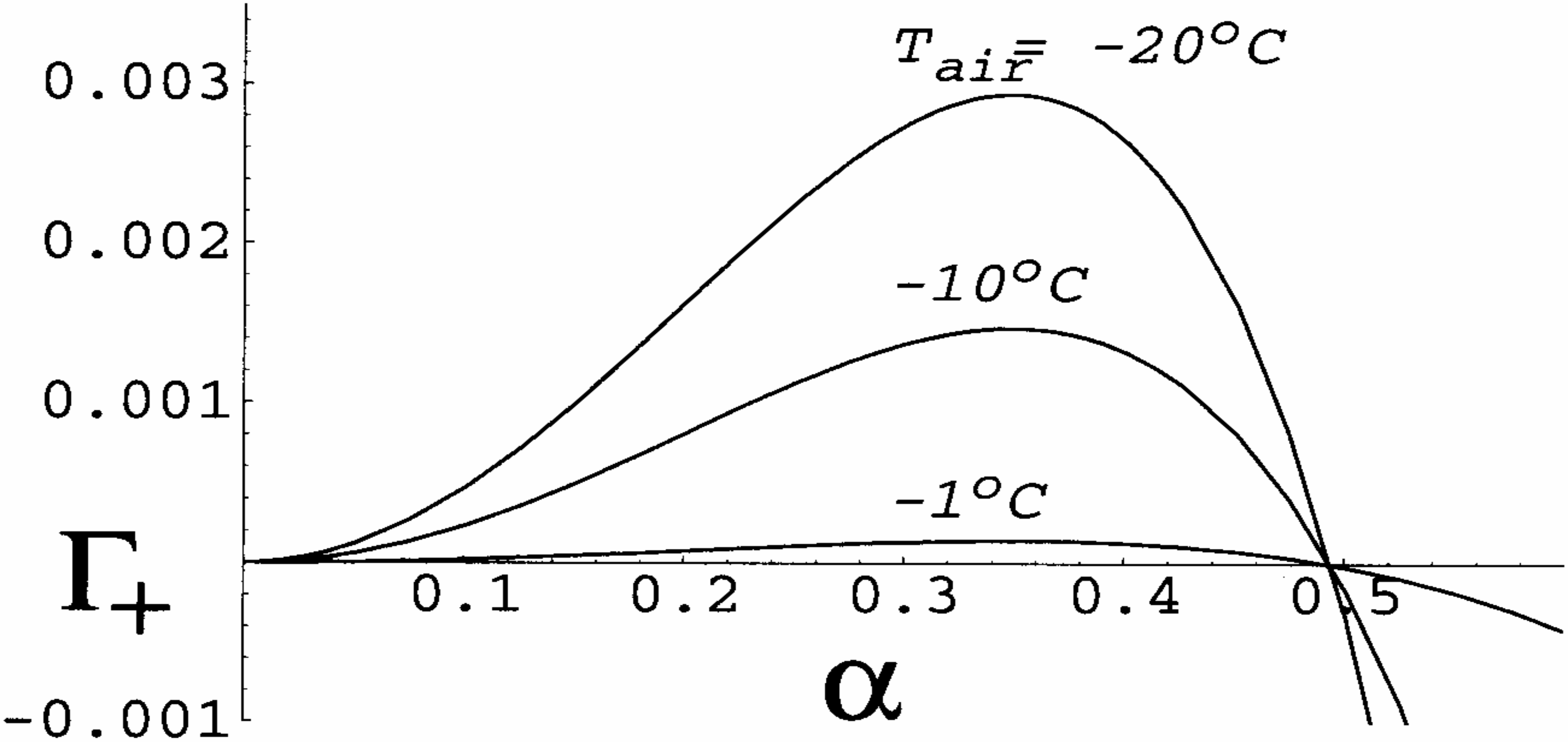
➢Soil type	➢Wind speed
➢Moisture content	➢Snow depth
➢Permafrost table	➢Vegetation cover
➢Air temperature	➢Rate of freezing

Soil Type Effect on Frost-Boils

Silts promote frost boils more than sands and clays owing to an optimal ability to generate significant heave pressure while maintaining sufficient soil permeability

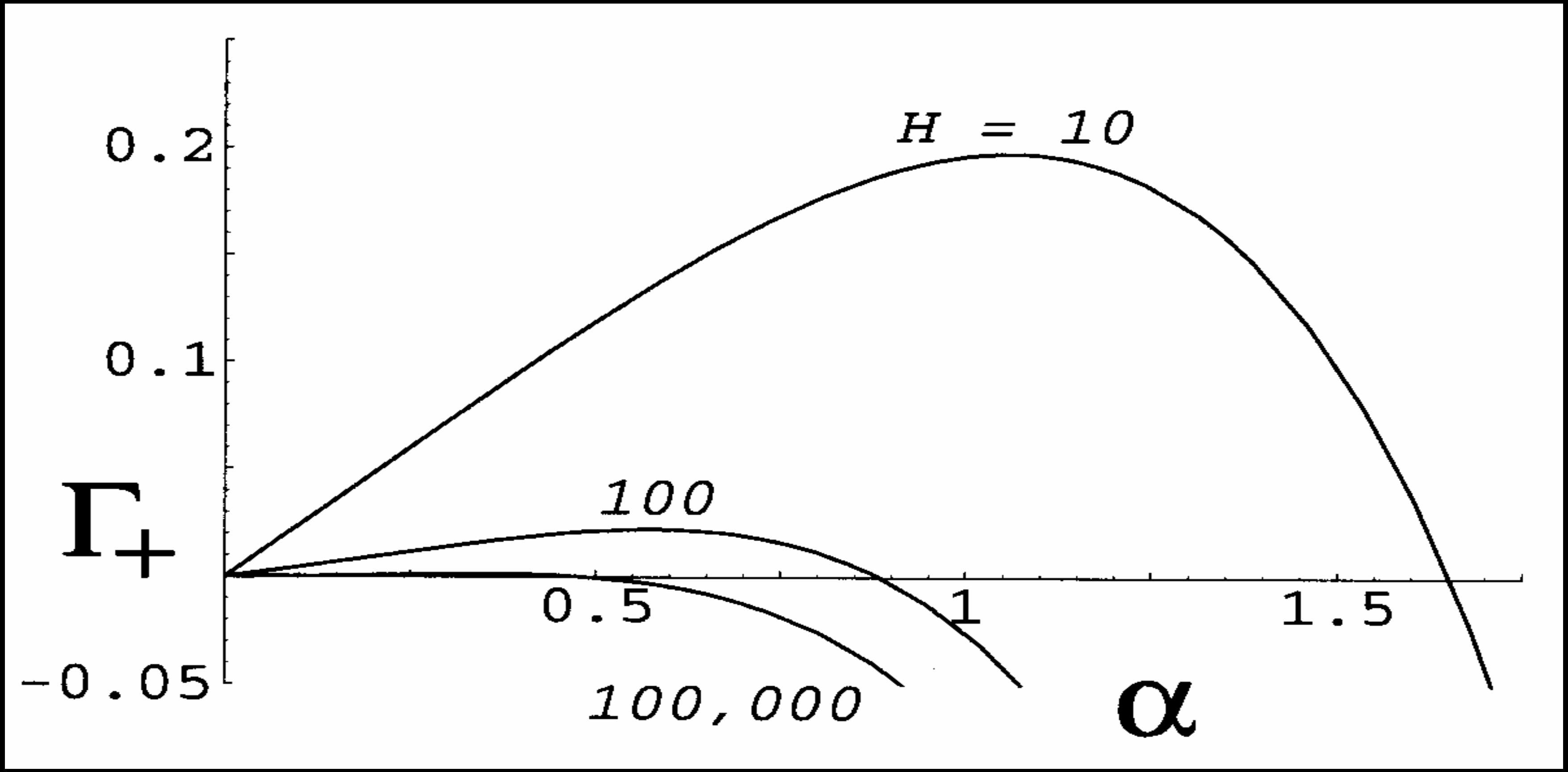


Air Temperature Effect on Frost Boils



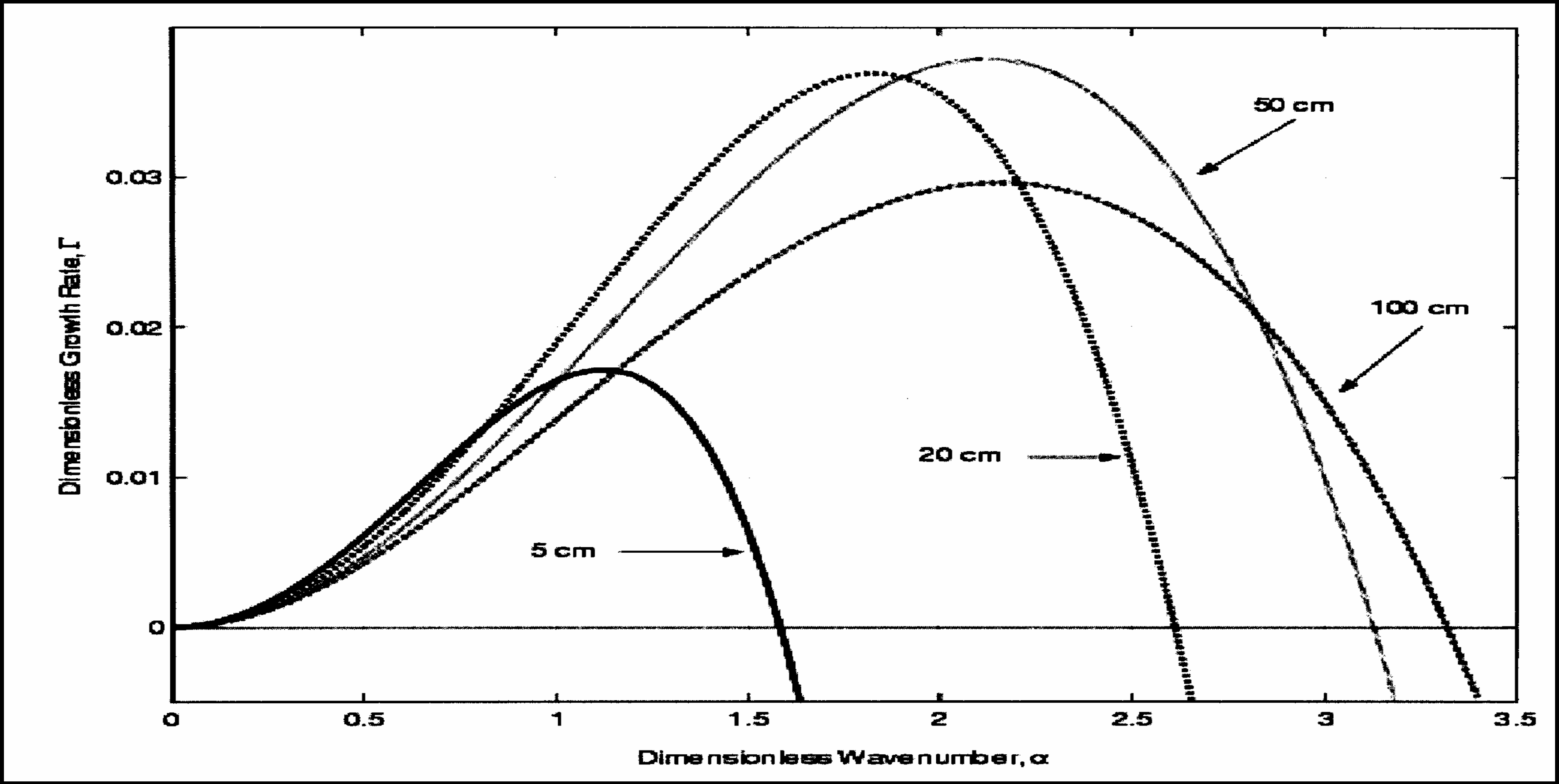
Colder climate conditions promote frost-boil growth.

Wind Effect on Frost Boils



Wind speed enters model through the heat- transfer coefficient (HTC), which increases monotonically with wind speed – interestingly, the propensity to form frost boils is not a monotonic function of the HTC!

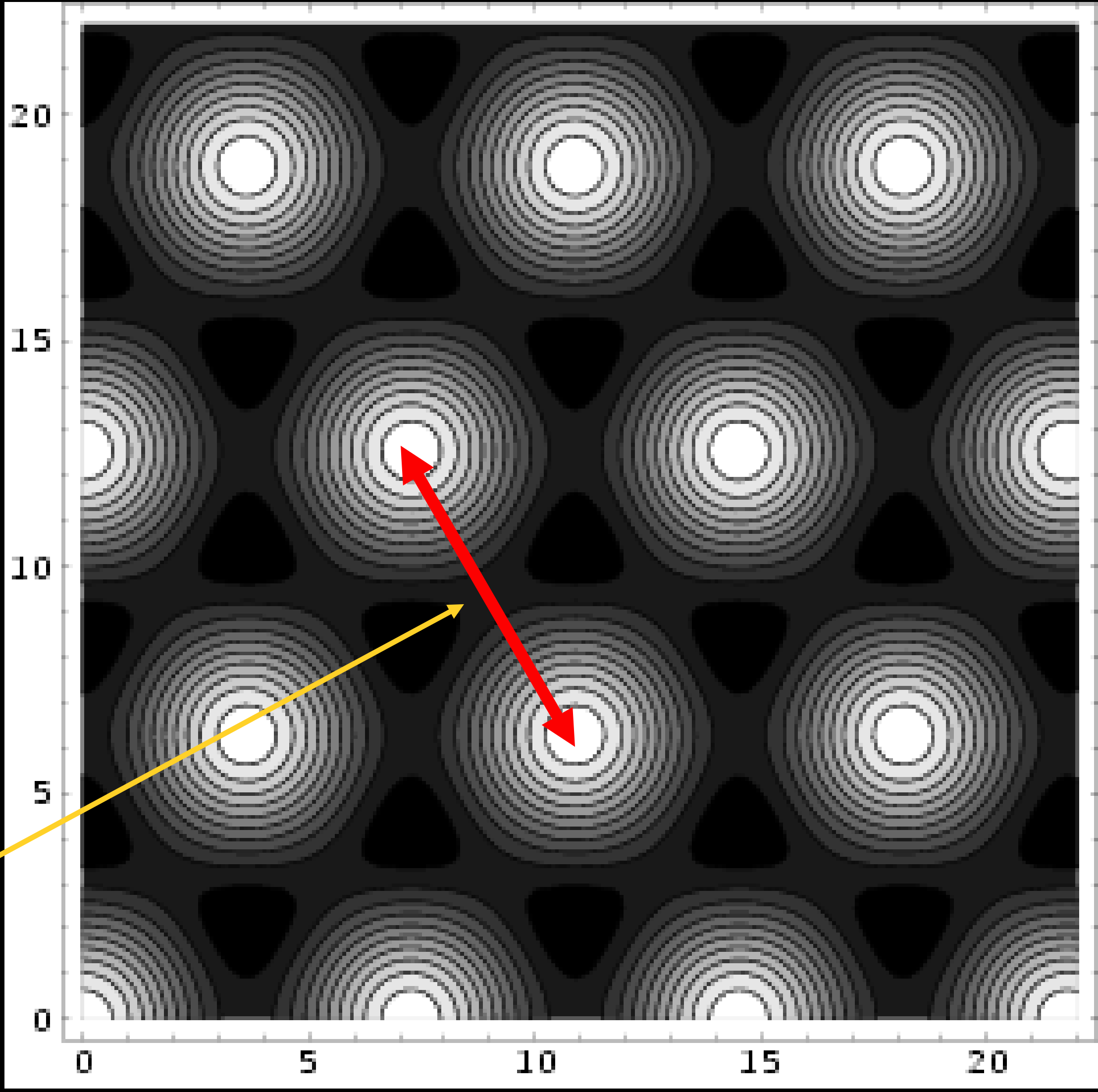
Snow Depth Effect on Frost Boils



Snow depth has effect similar to HTC – small to moderate snow depths (5-50 cm) promote frost boils, whereas large depths (> 50 cm) provide an insulating effect that retards frost boils.

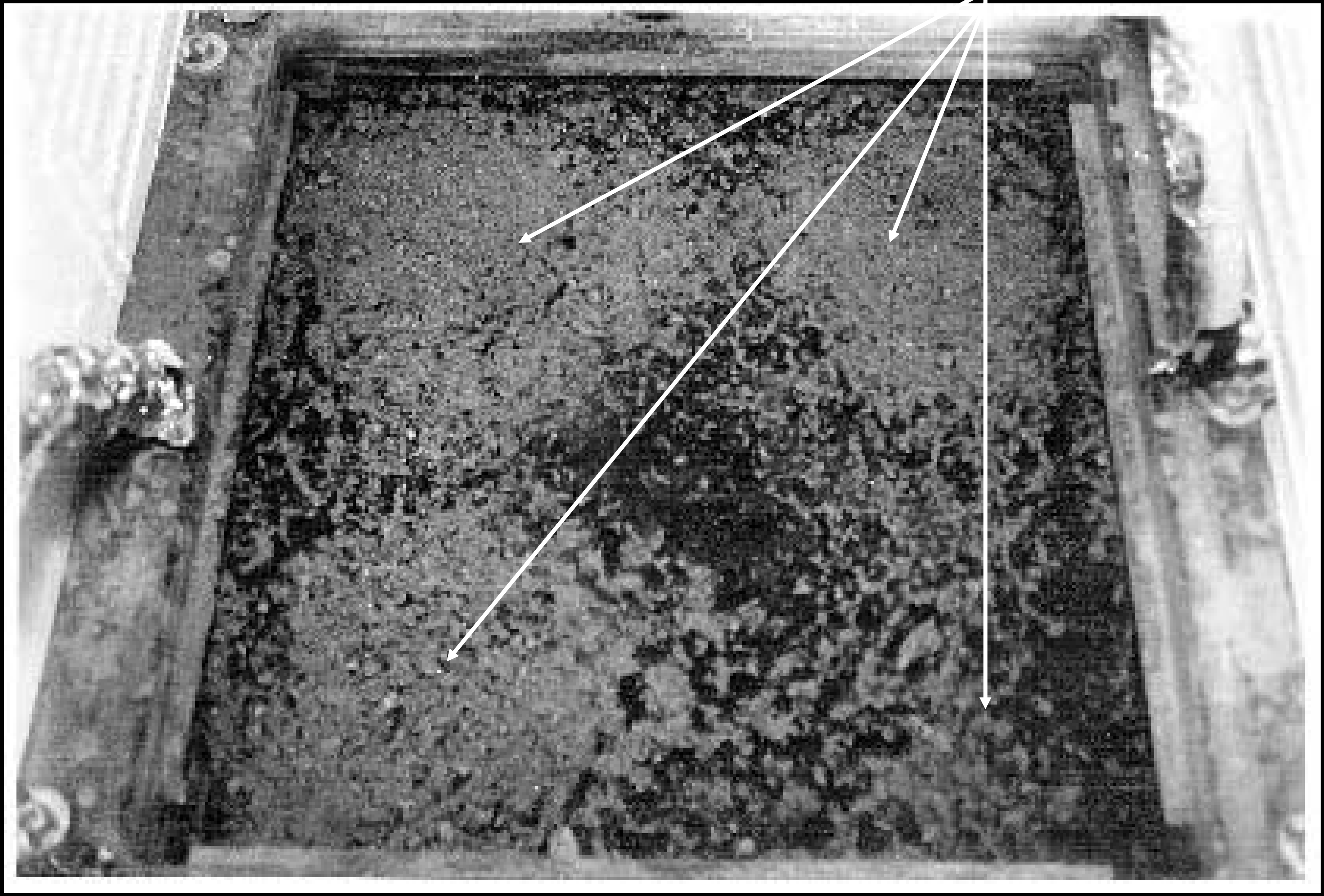
Computer Simulation of Frost Boils

Patterns arising from DFH can take shape of stripes, squares, rectangles, equilateral triangles, and hexagons – the latter are preferred



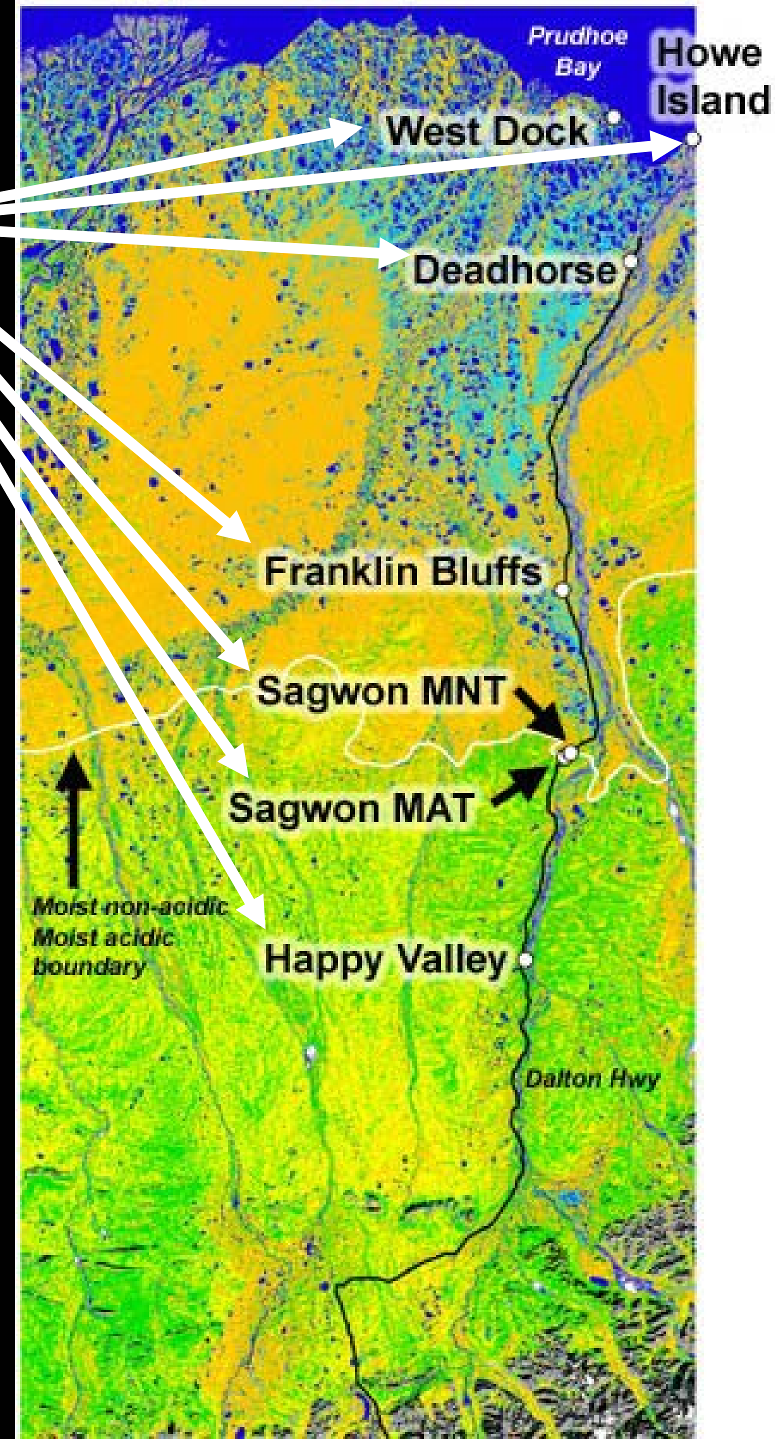
Wavelength predicted by stability theory

Laboratory Studies of Frost Boils

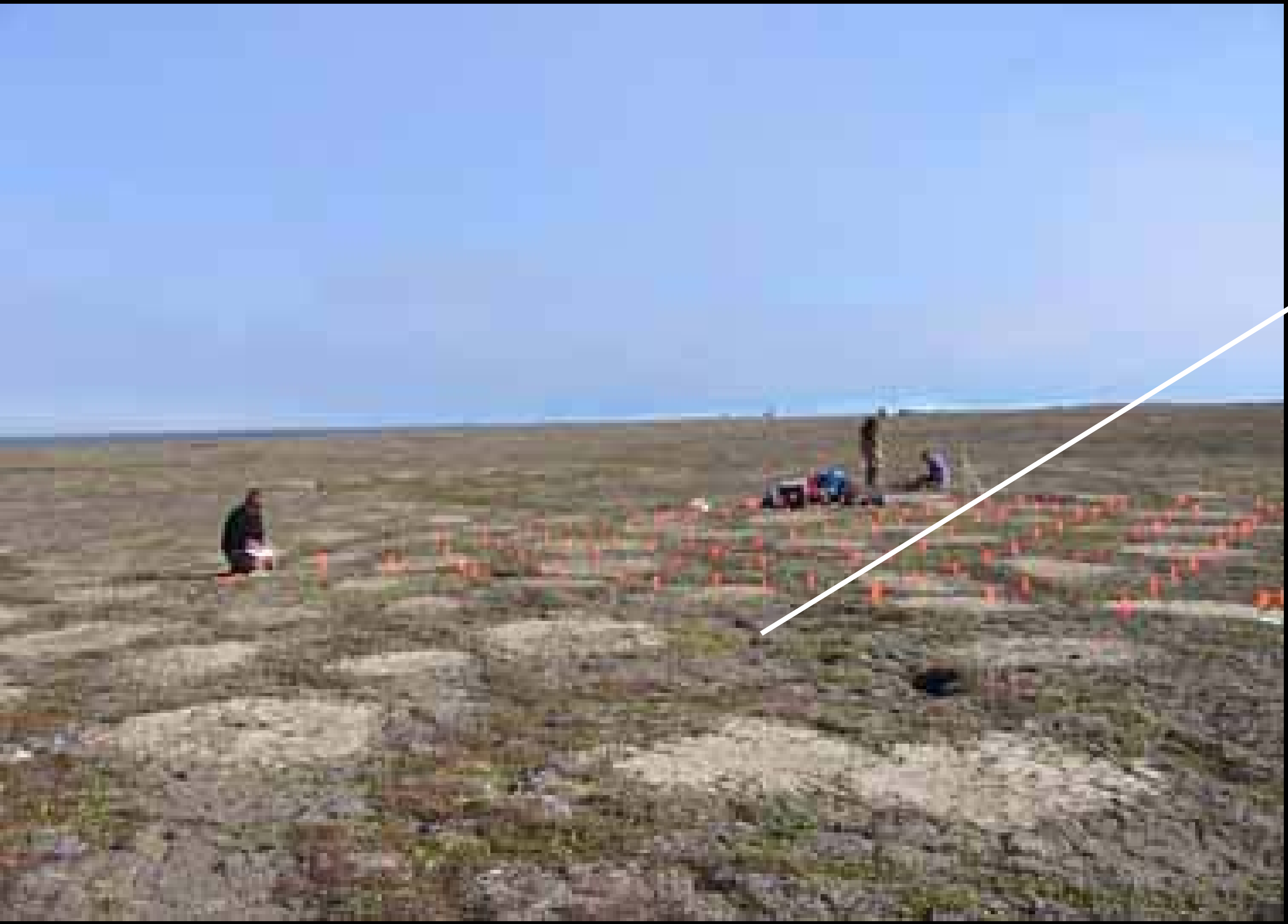


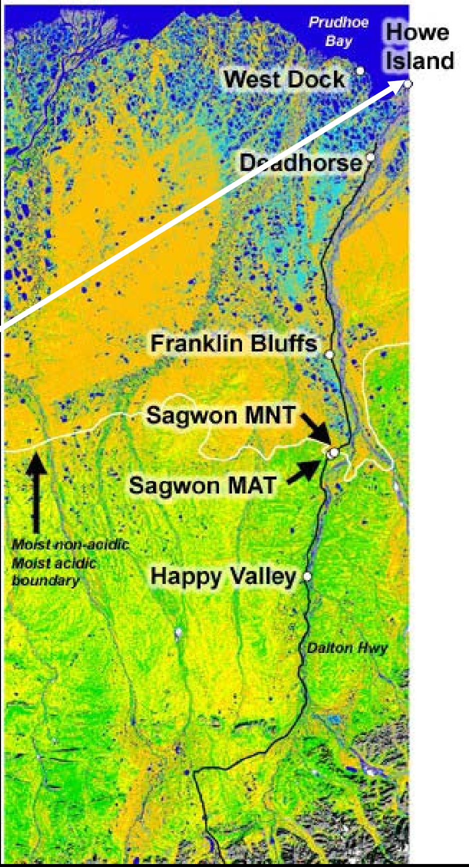
Field Studies of Frost Boils

Field Sites

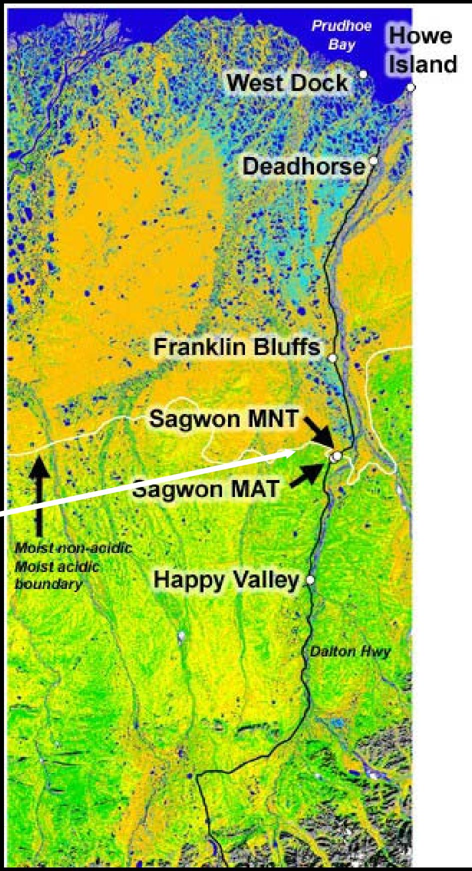


Active Frost Boils

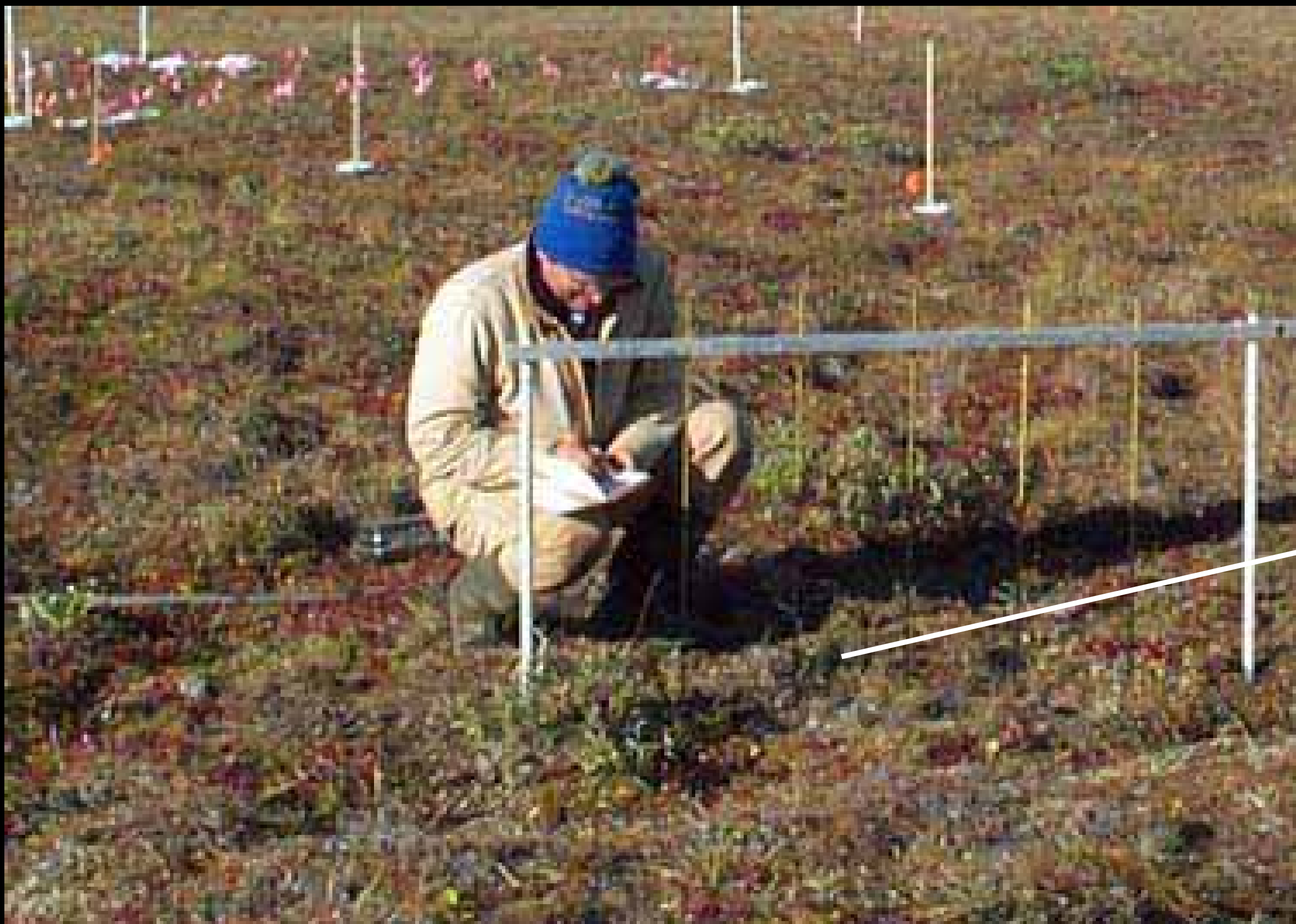


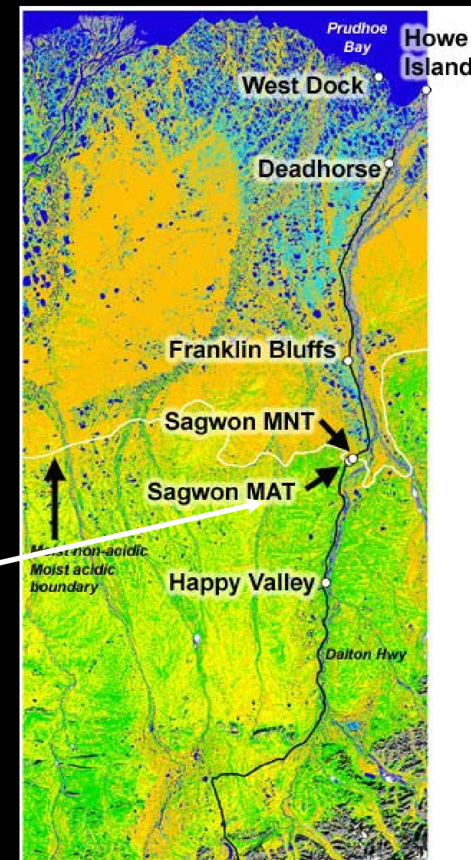


Frost Boils Becoming Less Active



Inactive Frost Boils





Evidence of Relict Frost Boils