Outline

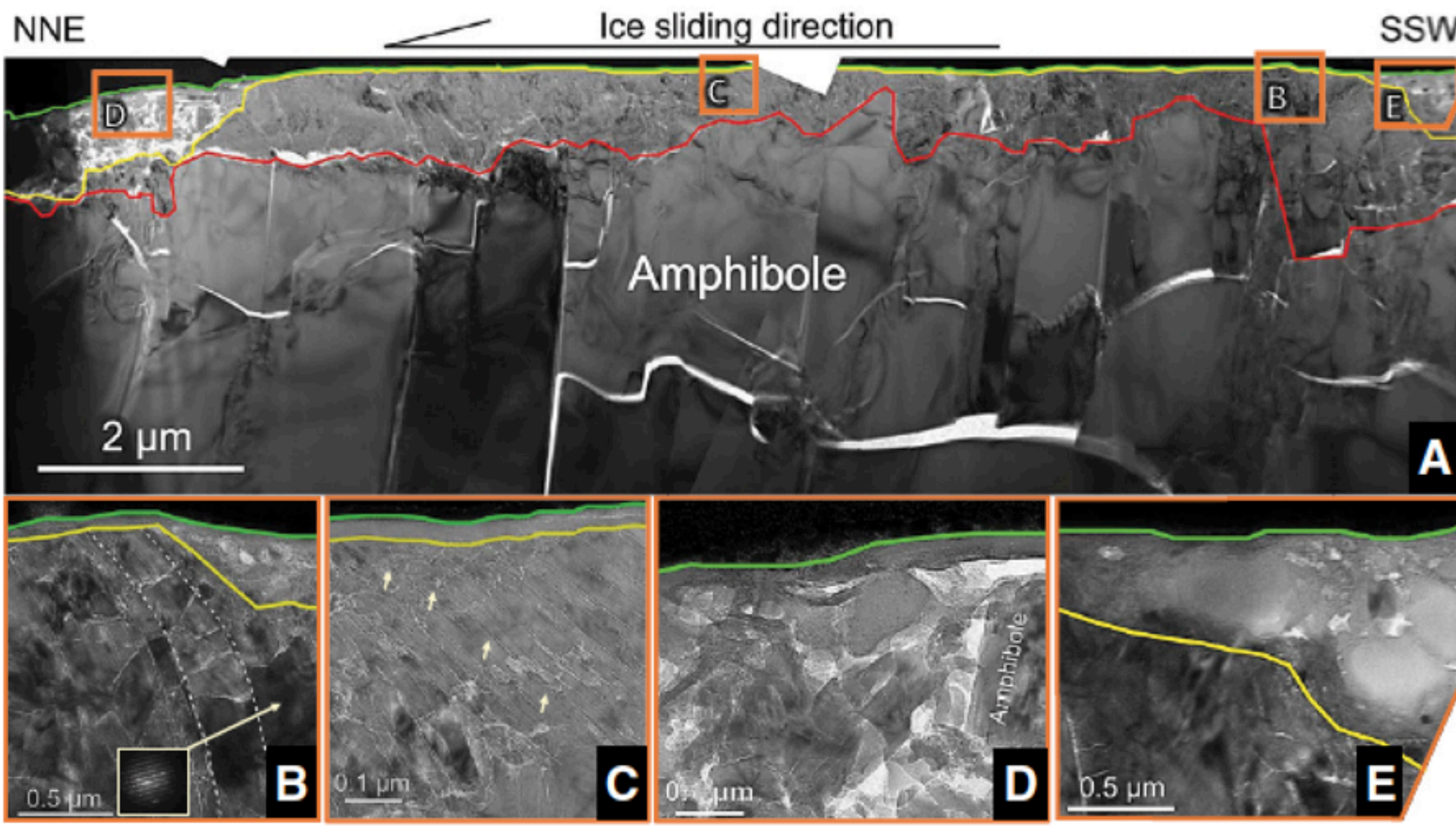
- Products: large to small
- Insights into processes
  - glacial (regelation, sliding)
  - erosional mechanisms (abrasion, quarrying, etc.)
  - Rates
- Implications

Background: Glacial polish with nano-scale chemcial coating

Physico-Chemical case-hardening: nano-scale particles filling micro-cracks and sealing the surface (2017, Geology)

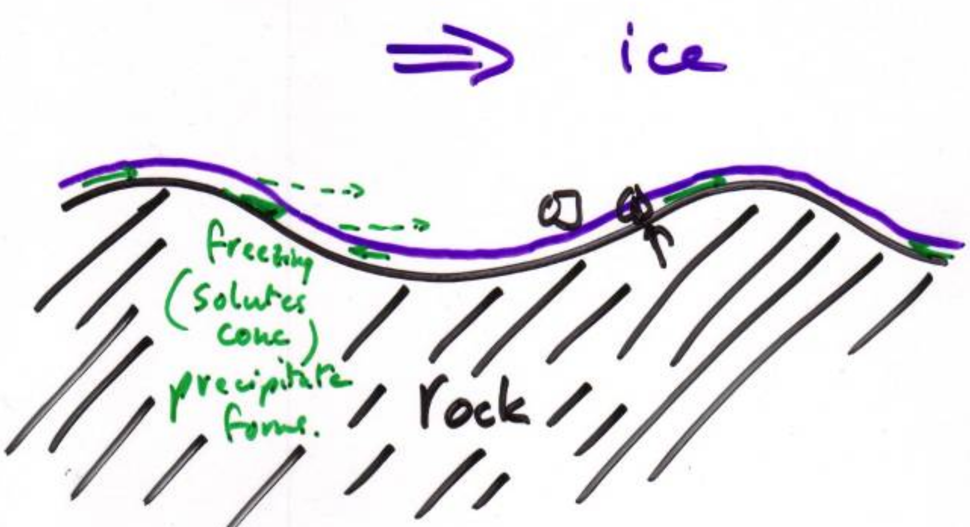
The coating layer of glacial polish

Shalev Siman-Tov[1], Greg M. Stock[2], Emily E. Brodsky[1], and Joseph C. White[3]



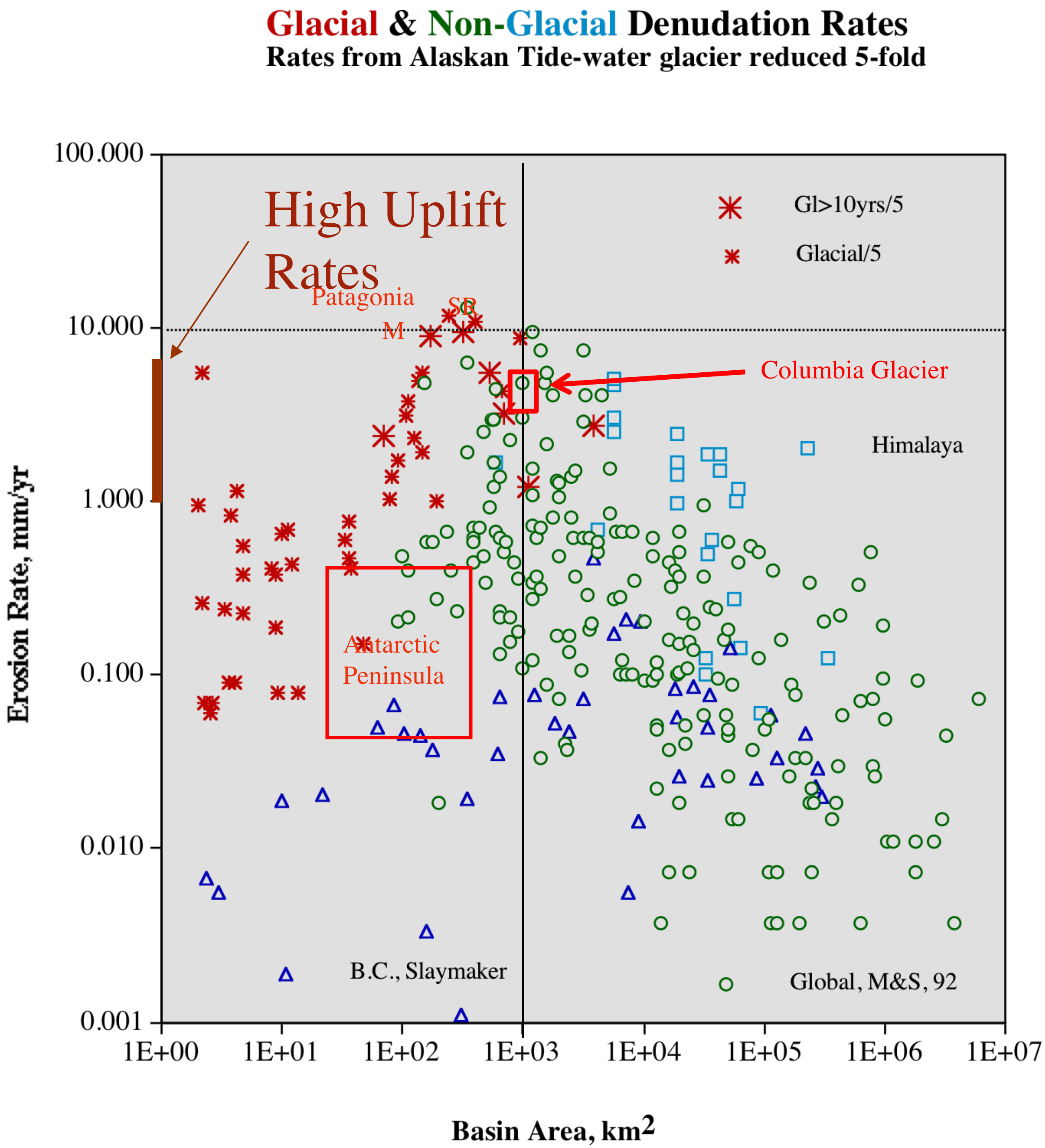
Sliding physics (regelation) & suglacial chemical processes

Sliding over small bumps is dominated by regelation, which involves melting/freezing, and water flow in a thin basal film. Solutes in the water film that are rejected during the freezing process can exceed saturation, causing chemical precipitation.

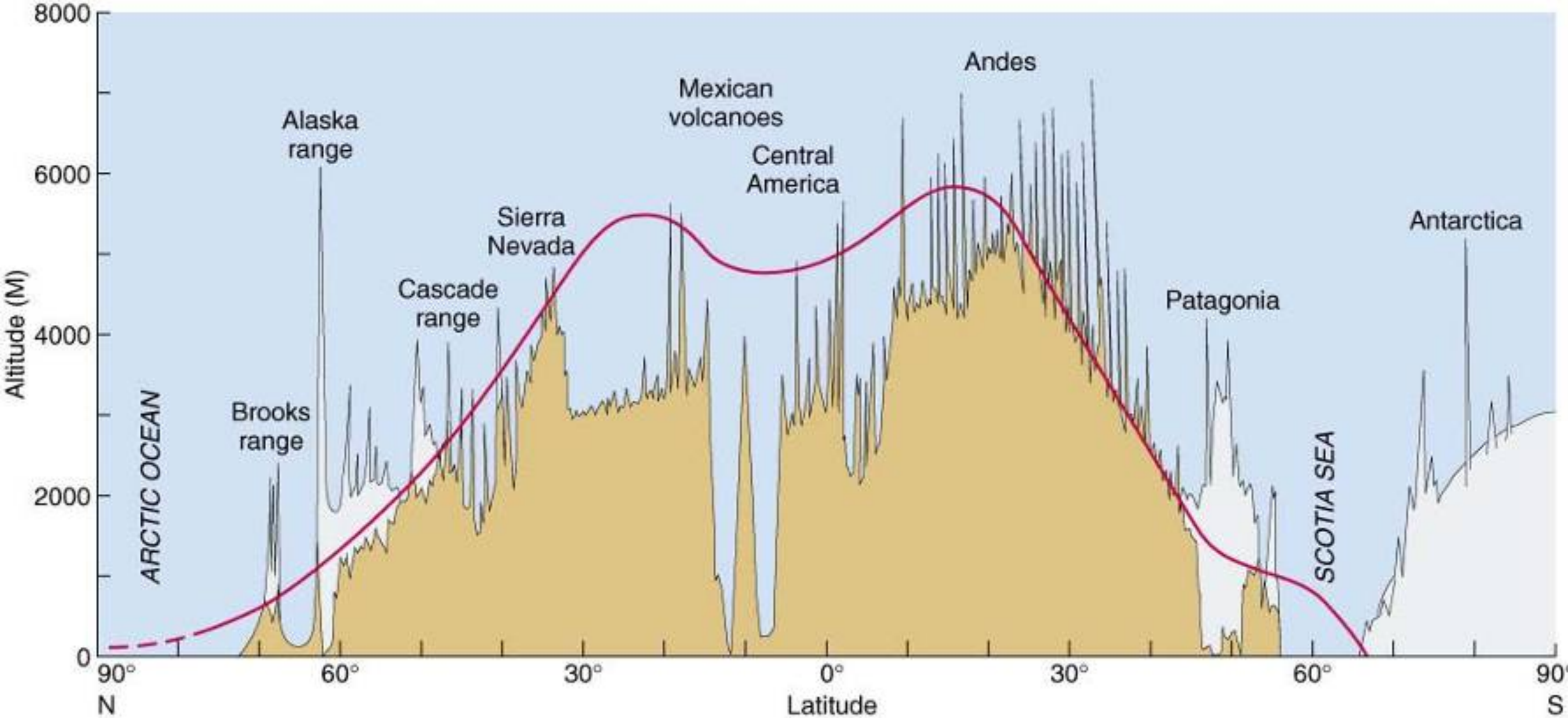


Contrasting hydraulic systems: microscopic, saturated films, where the white carbonate coatings cover the bedrock, traversed by interconnected cavities full of under-saturated water as evident from the dissolution features (buff-colored argillite seams), Blackfoot Glacier flowed from left (Montana)

Global erosion **rates**



Glacial Buzz saw



S.C. Porter

Equilibrium Line Altitude "ELA"

Near Polar Regions: Alpine topography at sea level, Lofoten Islands, Norway

Near the Equator, the World's Highest Mountains, Mt Everest in center

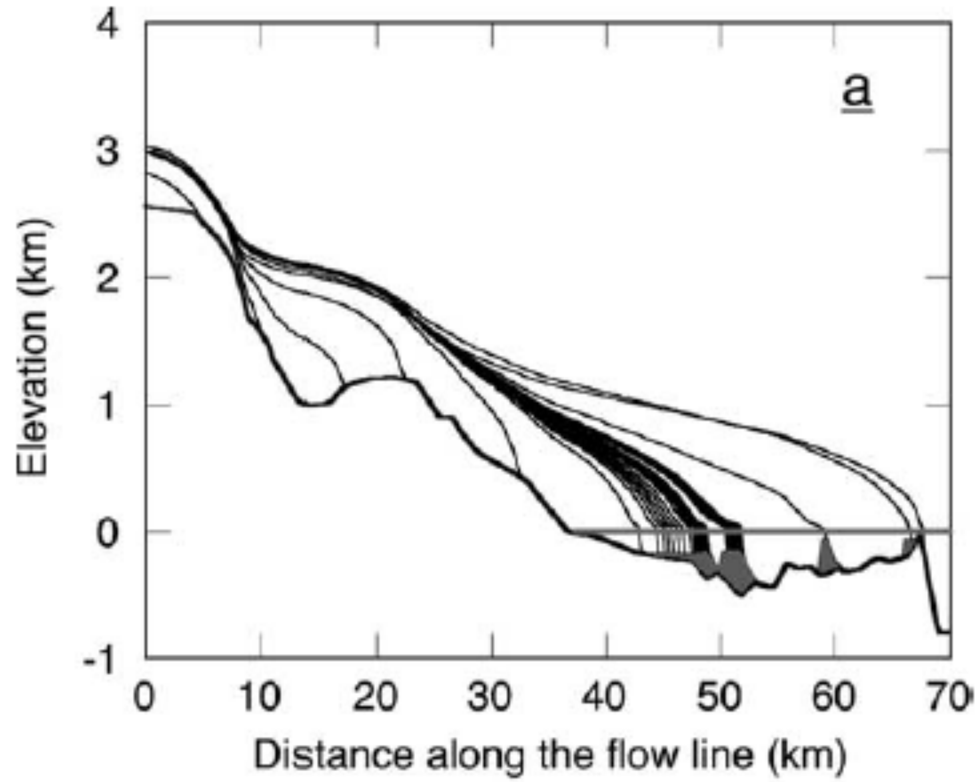
The ridge lower with the valleys. 2015 landslide, Taan Fjord below Mt. St. Elias, Alaska. *The mountain fell, 150 million tons of rock shooting down….displacing water that surged uphill as a tsunami, reaching ~600 feet above”*

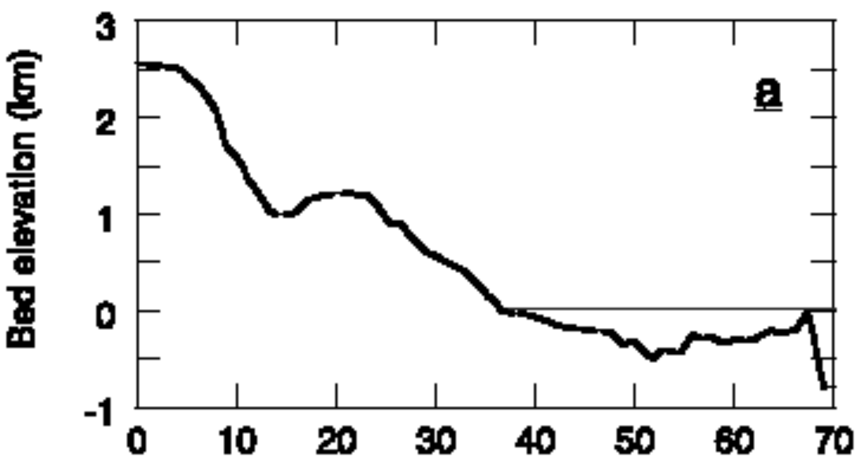
Sediments, the product of glacial erosion, and associated landforms: braided rivers, Gilbert deltas and turquoise waters, Peyto Lake, Banff NP, Alberta

Controls on advance of tidewater glaciers: Results from numerical modeling applied to Columbia Glacier

F. M. Nick, C. J. van der Veen and J. Oerlemans

(JGR, 112, F03S24, doi:10.1029/2006JF000551, 2007)





"The results suggest that irrespective of the calving criterion and accumulation rate in the catchment area, it is impossible for the glacier terminus to advance into deeper water (>300 m water depth) unless sedimentation at the glacier front is included."

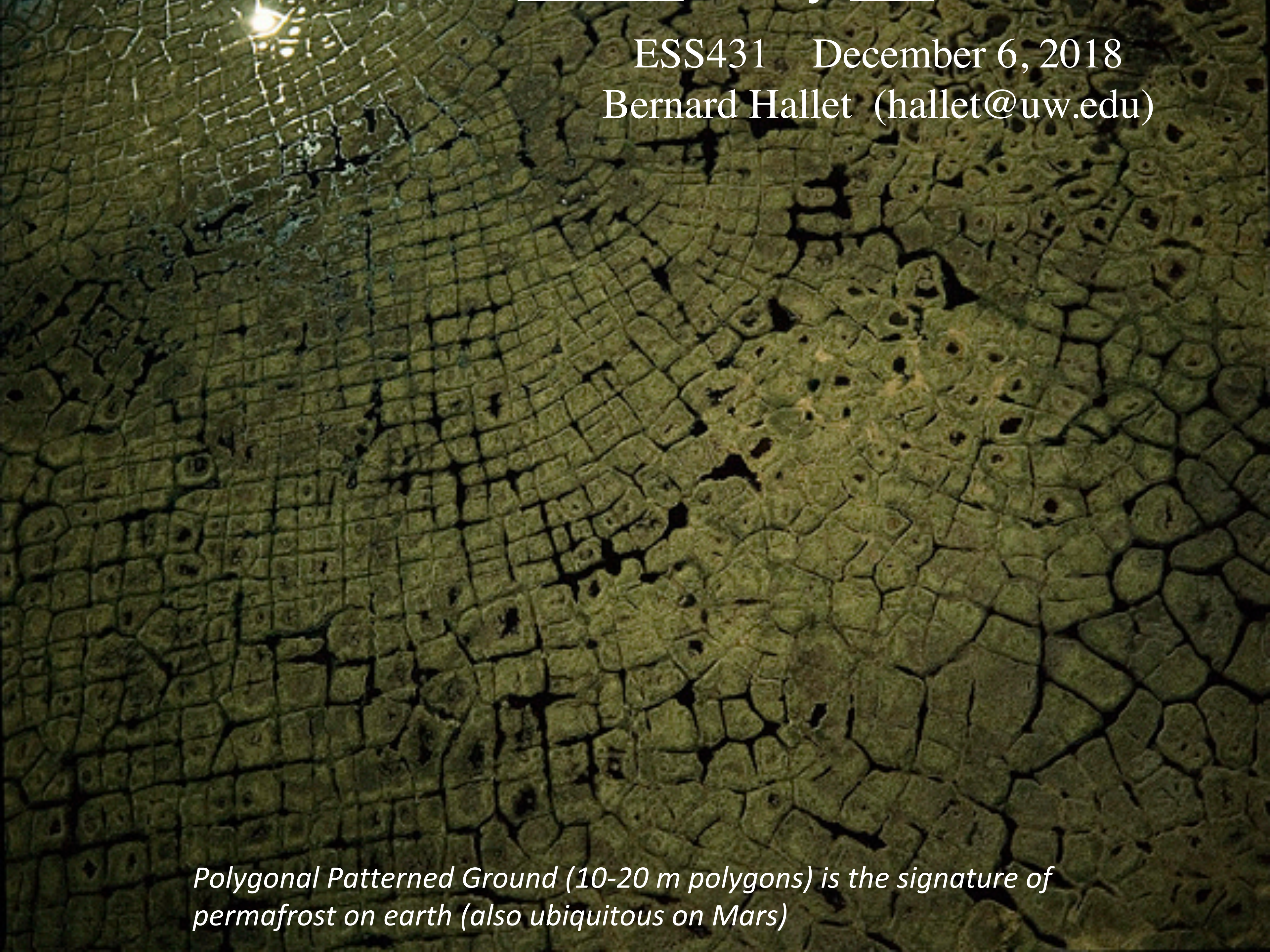
Summary

- Insights into glacial erosion mechanisms: quarrying, abrasion, chemical processes
- Introduction to ideas, models, and data: model validation is sparse
- Products of erosion: from scratches to spectacular valleys & fjords; massive amounts of sediment
- Rates of erosion: unsurpassed but highly variable
- Diverse roles of glacial erosion: from modulating glacial motion & fluctuations, to shaping much of the terrain we live on

Thank you!

ESS431 December 6, 2018

Bernard Hallet (hallet@uw.edu)



Polygonal Patterned Ground (10-20 m polygons) is the signature of permafrost on earth (also ubiquitous on Mars)

Permafrost: brief intro

Thermal regime & the warming Arctic

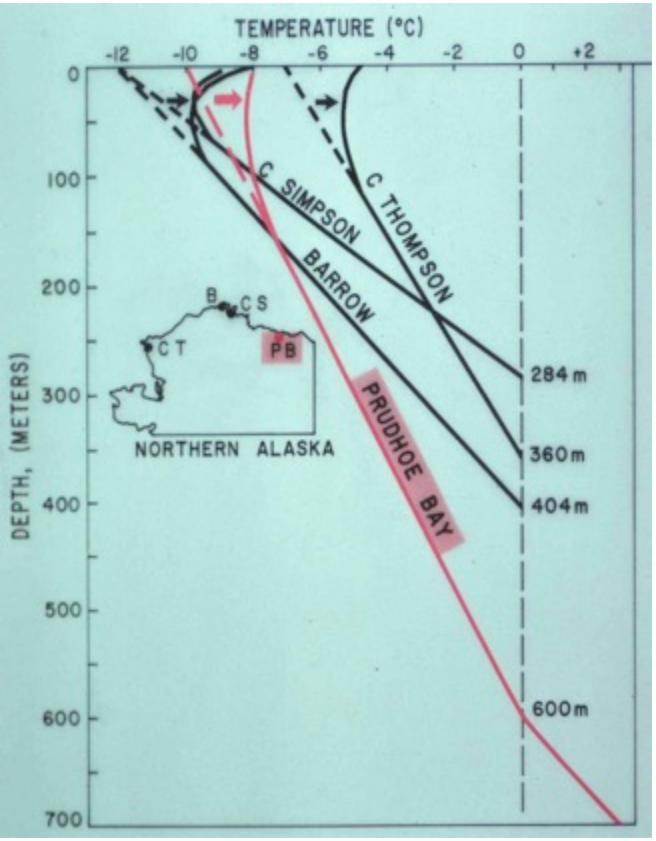
Soil is well known to expand, heave, and crack as it freezes but why and why it matters?

Patterned ground

Pingos, rock glaciers, etc

Mars, the permafrost planet

Permafrost thermal regime
Permanently frozen ground



Note that the frozen ground records the ongoing warming over the last century, long before instruments were available in the North

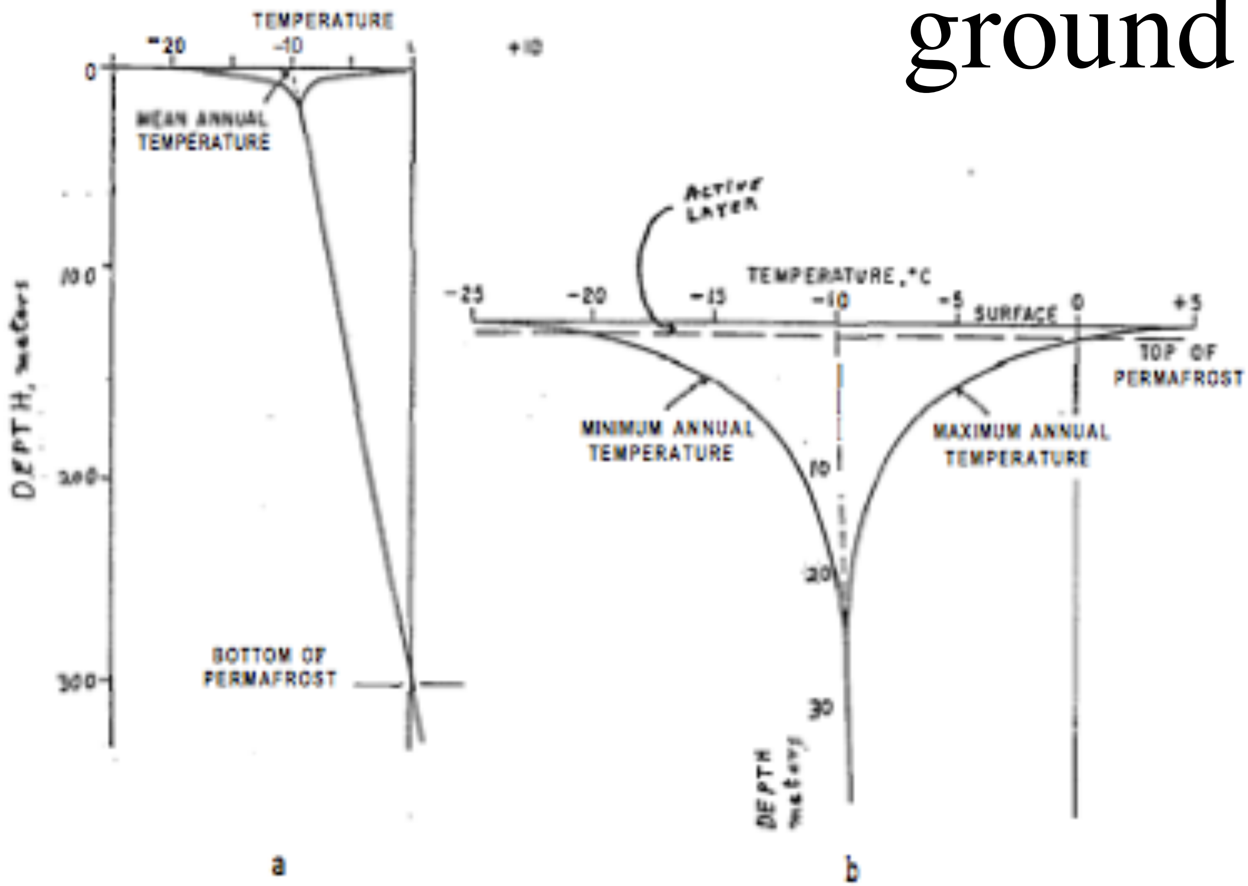
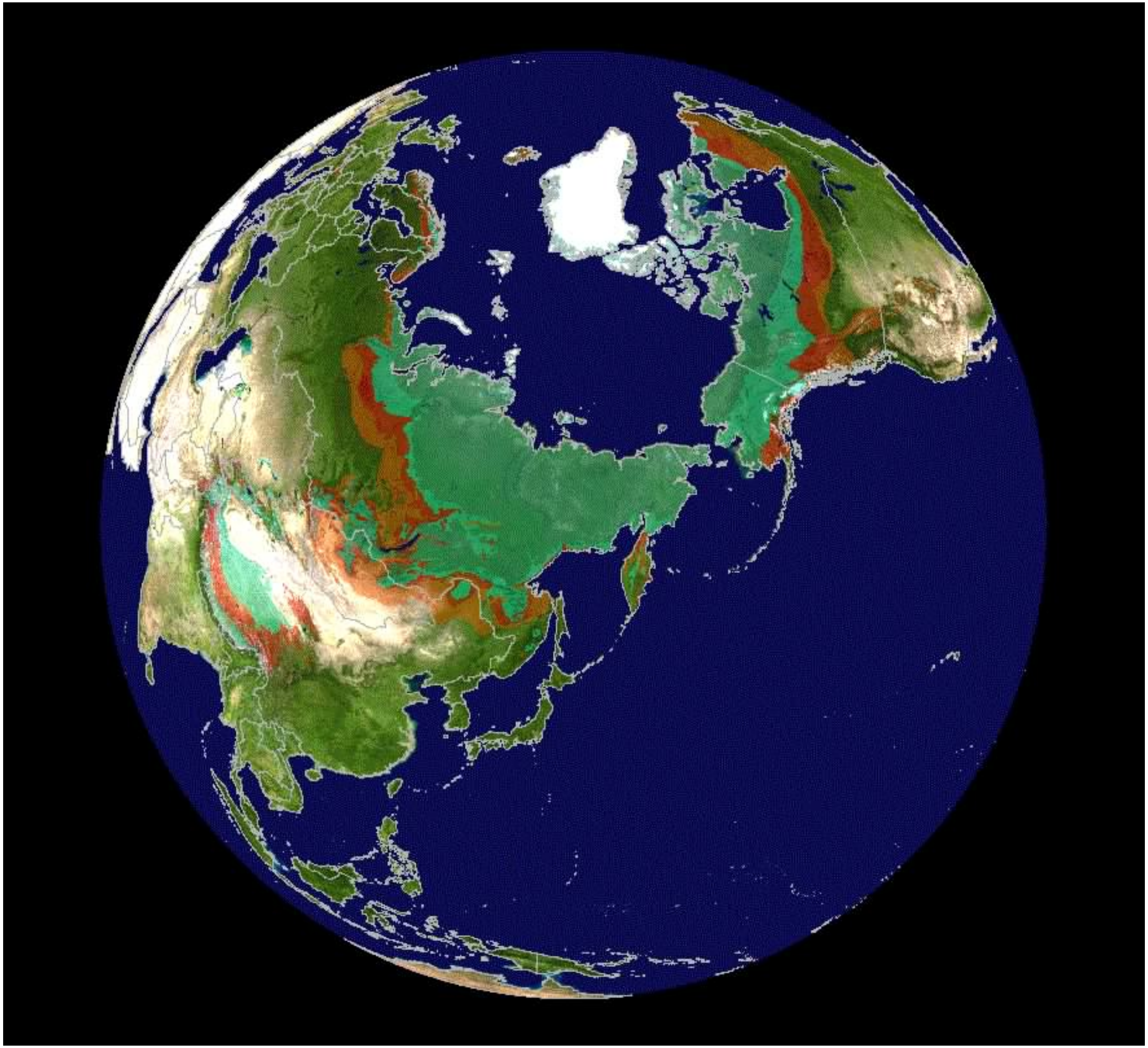
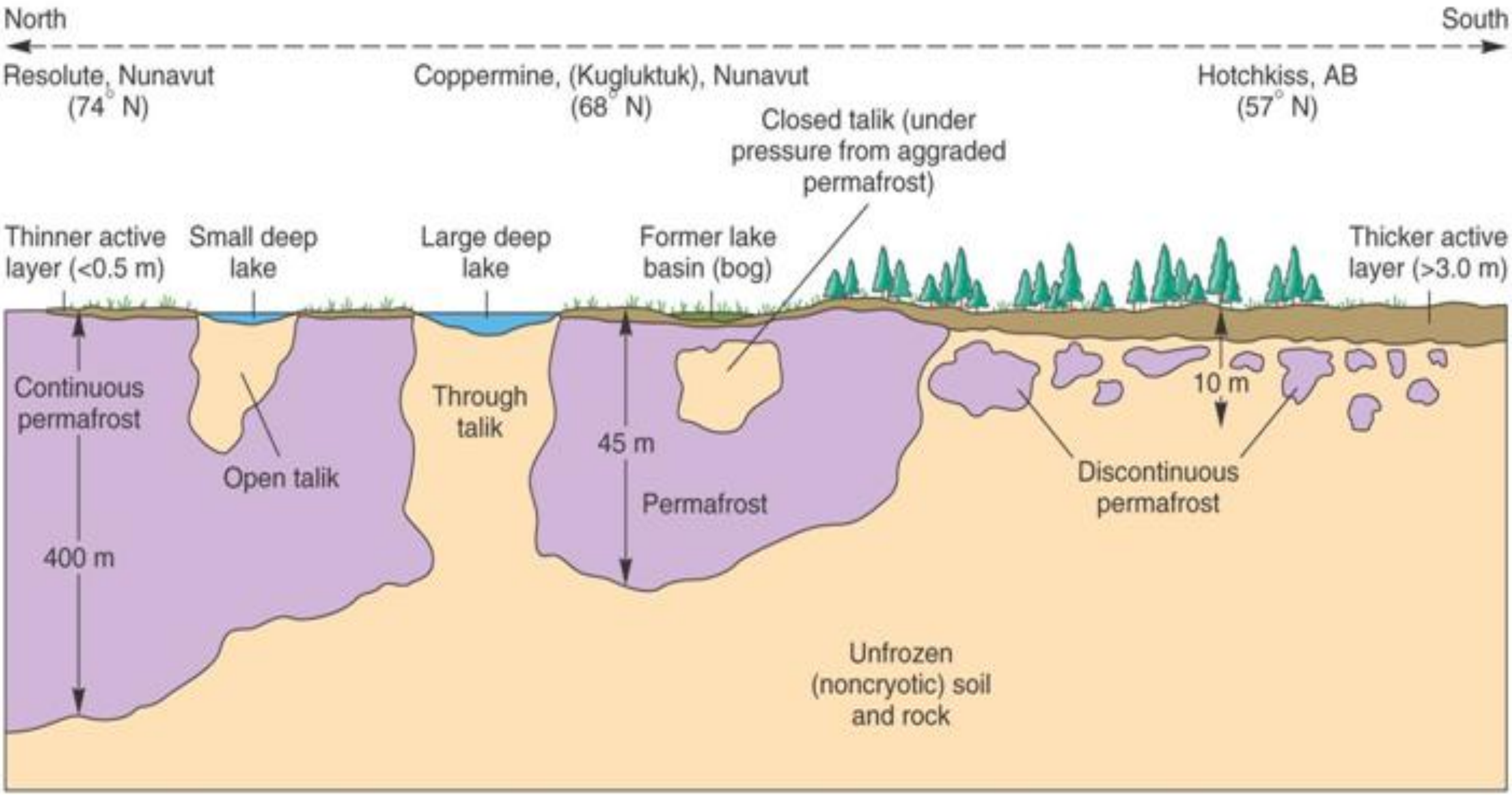


FIG. 2. Relationships between temperature and depth showing how the lower limit (a) and upper limit (b) of permafrost are established. Shown for ground surface temperature with seasonal amplitude of 15°C, mean, T_m, of -10°C, and geothermal gradient of 1°C per 30 m.



Permafrost Types and Depths



The Washington Post

+ More

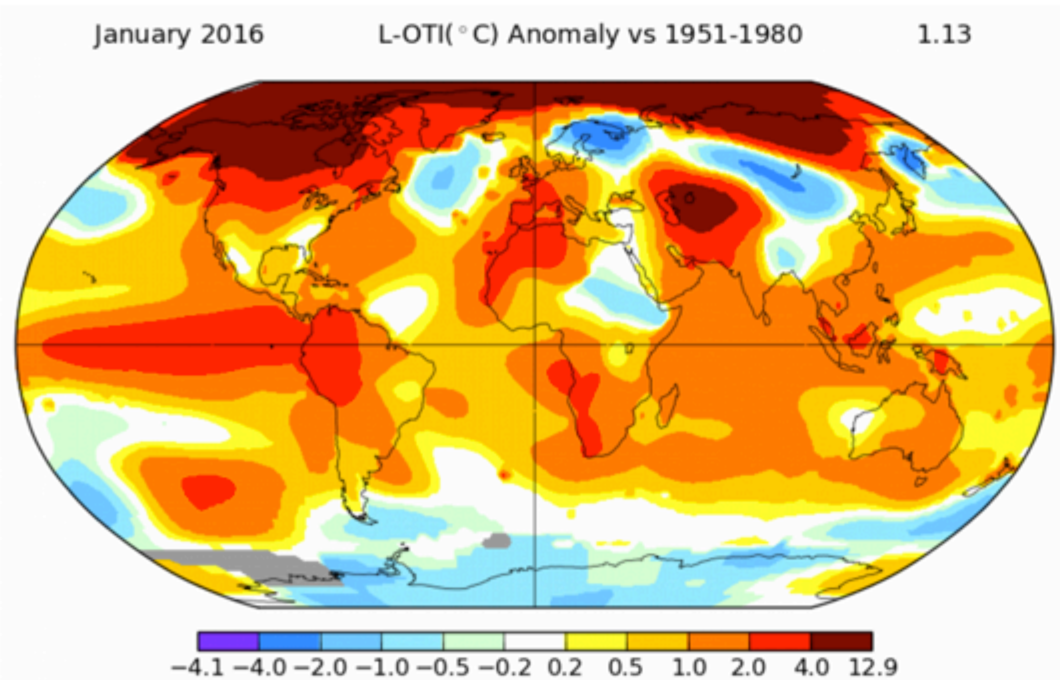
http://wpo.st/nHOH1

Energy and Environment

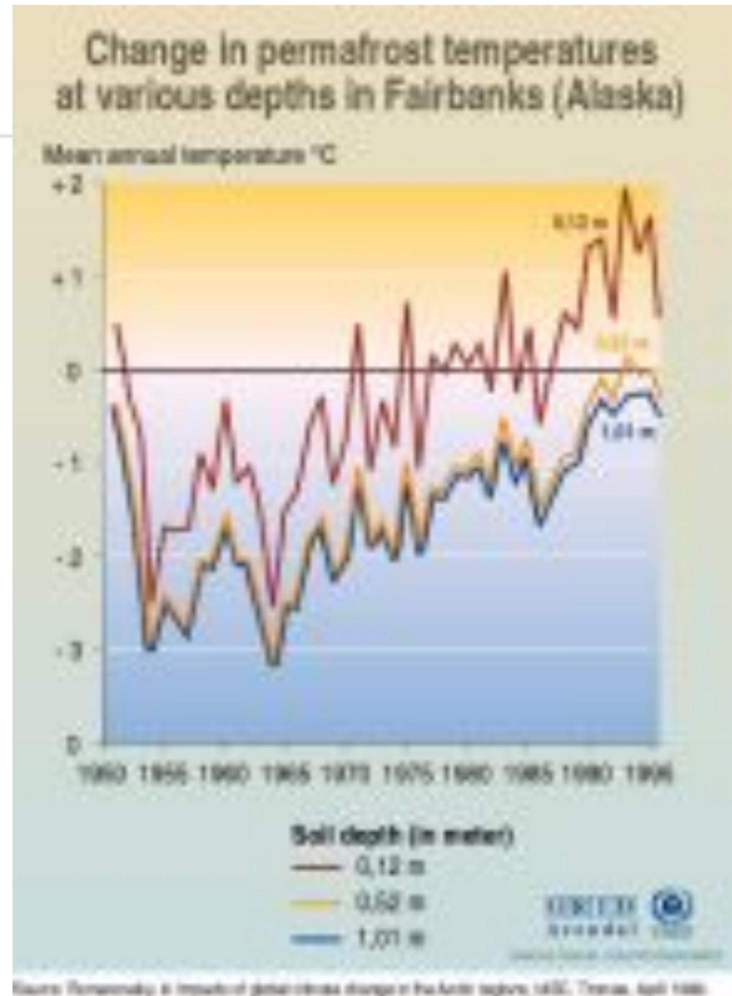
Scientists are floored by what's happening in the Arctic right now

A | 3131 | Save for Later | Reading List

By Chris Mooney February 18 Follow @chriscmooney

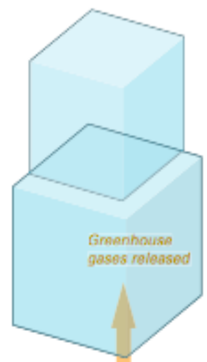


Temperature anomalies for January, 2016. NASA Goddard Institute for Space Studies

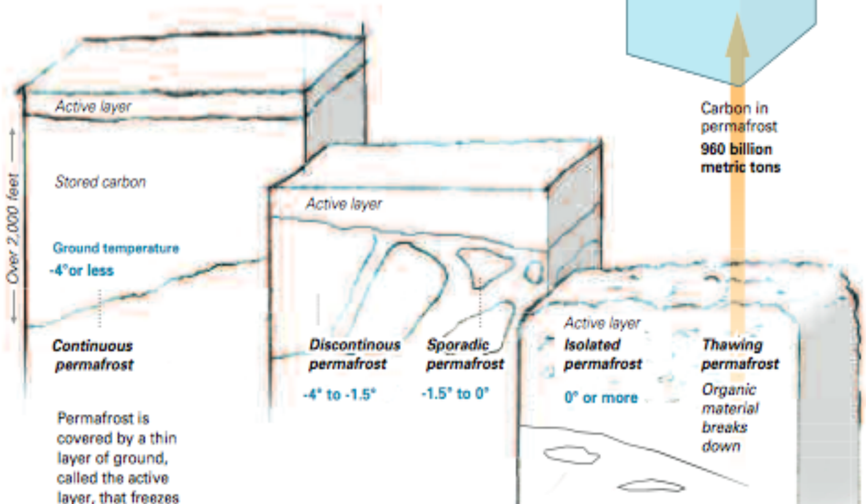


A Threatening Thaw

Permafrost is frozen ground that remains at or below 32° F (0° C) for two or more years. Most of the world's permafrost has been frozen for centuries or millennia, trapping vast amounts of carbon in organic material. As global warming thaws the terrain, the released carbon dioxide and methane may help accelerate temperature rise. It's a potential time bomb—the amount of carbon stored in permafrost exceeds the volume already in the atmosphere.



TYPES OF PERMAFROST



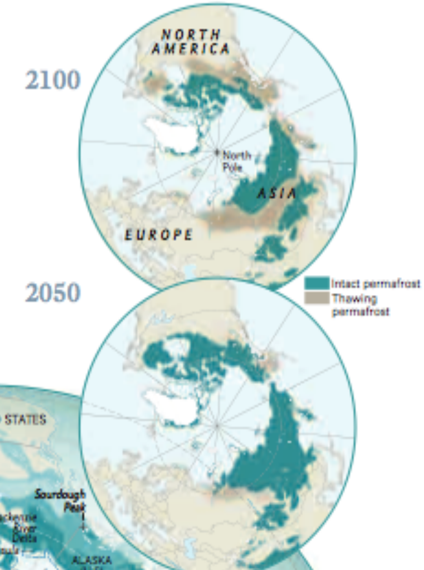
Permafrost is covered by a thin layer of ground, called the active layer, that freezes and thaws with the changing seasons. Plants can only grow within this layer, up to 12 feet thick.

Where the average annual air temperature is only slightly below freezing, permafrost ranges from discontinuous to sporadic, topped by a deeper active layer.

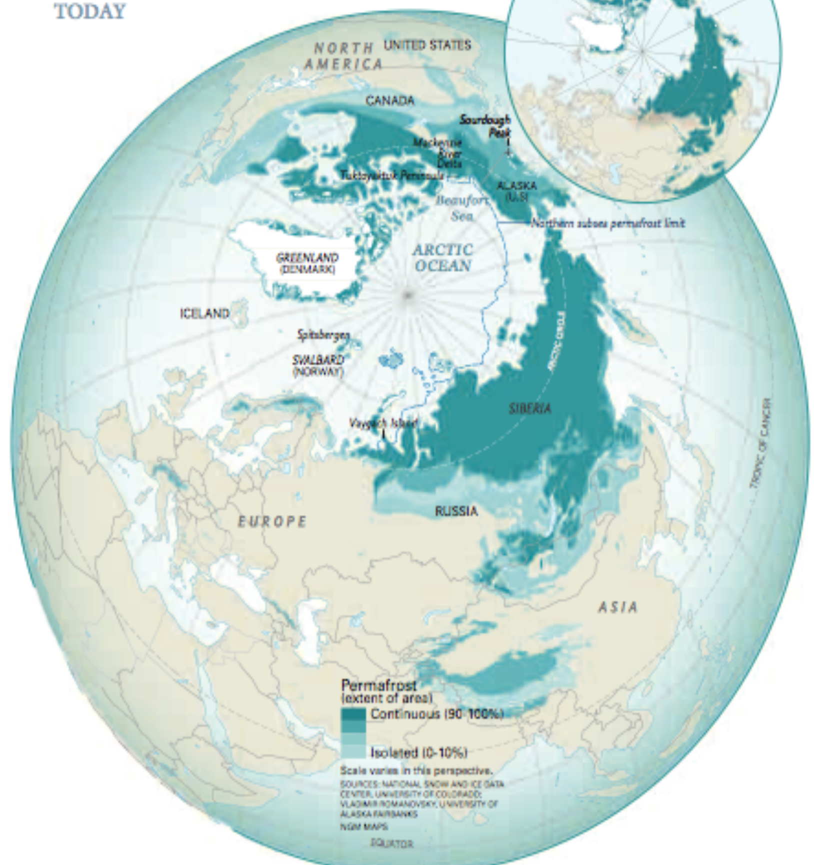
Isolated permafrost has a thicker, warmer active layer. All types of permafrost are being affected by shorter, milder winters. Increased microbial activiy speeds decomposition of organic matter, producing carbon dioxide and methane.

SOURCE: NATIONAL SNOW AND ICE DATA CENTER, UNIVERSITY OF COLORADO; KATEY WALTER, INSTITUTE OF ARCTIC BIOLOGY, UNIVERSITY OF ALASKA FAIRBANKS; U.S. ARCTIC RESEARCH COMISSION
NGM ART

The permafrost belt embracing Siberia, Scandinavia, northern Canada, and Alaska is experiencing the world's fastest rate of temperature increase. Today, permafrost occupies about 25 percent of the terrestrial Northern Hemisphere.



TODAY



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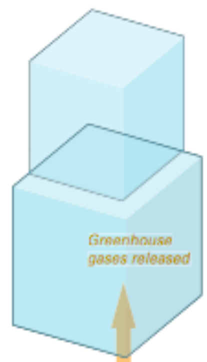
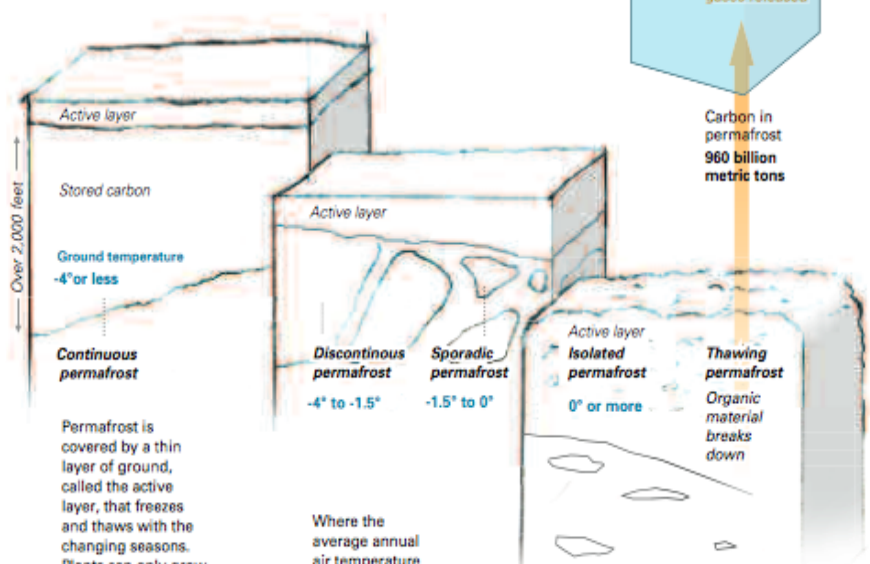
Global Carbon Mass in billions of tons

Atmosphere: 798

Permafrost: 960



TYPES OF PERMAFROST



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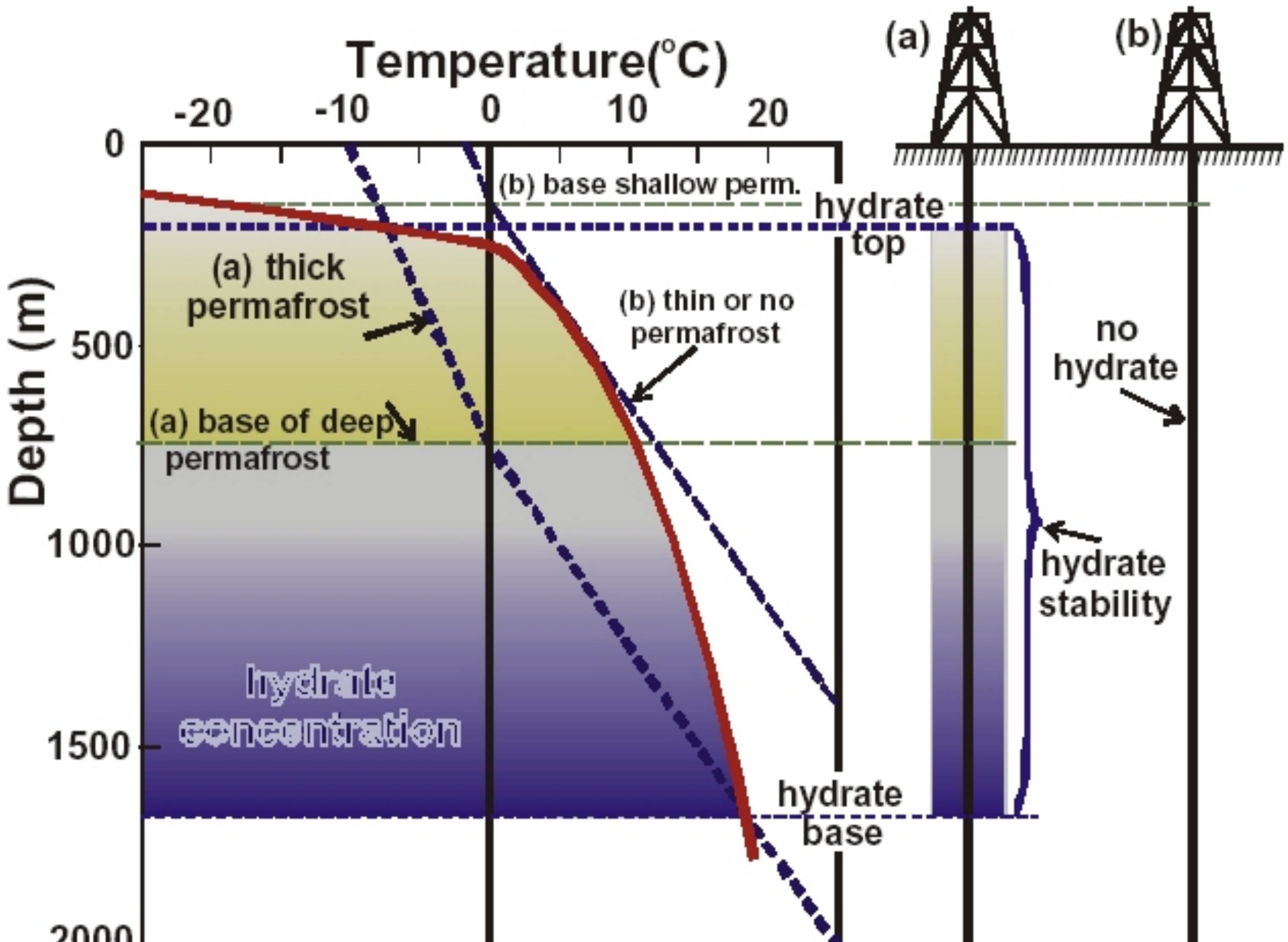
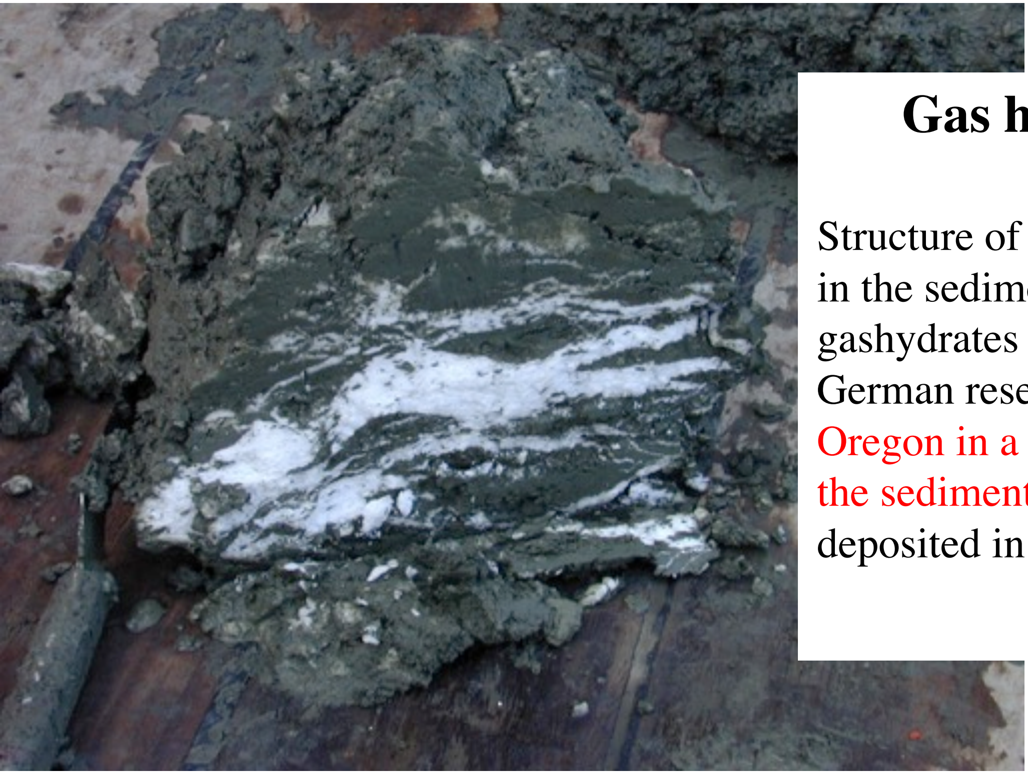
TODAY

2050

Perhaps, a bigger concern about warming permafrost: gas hydrates





Gas hydrate-bearing sediment, from the subduction zone off Oregon

Structure of a gas hydrate (methane clathrate) block embedded in the sediment of hydrate ridge, off Oregon, USA. The gashydrates have been found during a reaserch cruise with the German reseach ship FS SONNE in the subduction zone off Oregon in a depth of about 1200 meter in the upper meter of the sediment. The shown gas hydrate (white) has been deposited in thin layers into the sediment

Note: at a depth of 1200 m, ocean water slightly above 0° C is well within the methane hydrate stability field

"Estimates on how much energy is stored in methane hydrates range from 350 years' supply to 3500 years' supply based on current energy consumption. That reflects both the potential as a resource and how little we really know about the resource"
http://web.ornl.gov/info/reporter/no16/methane.htm

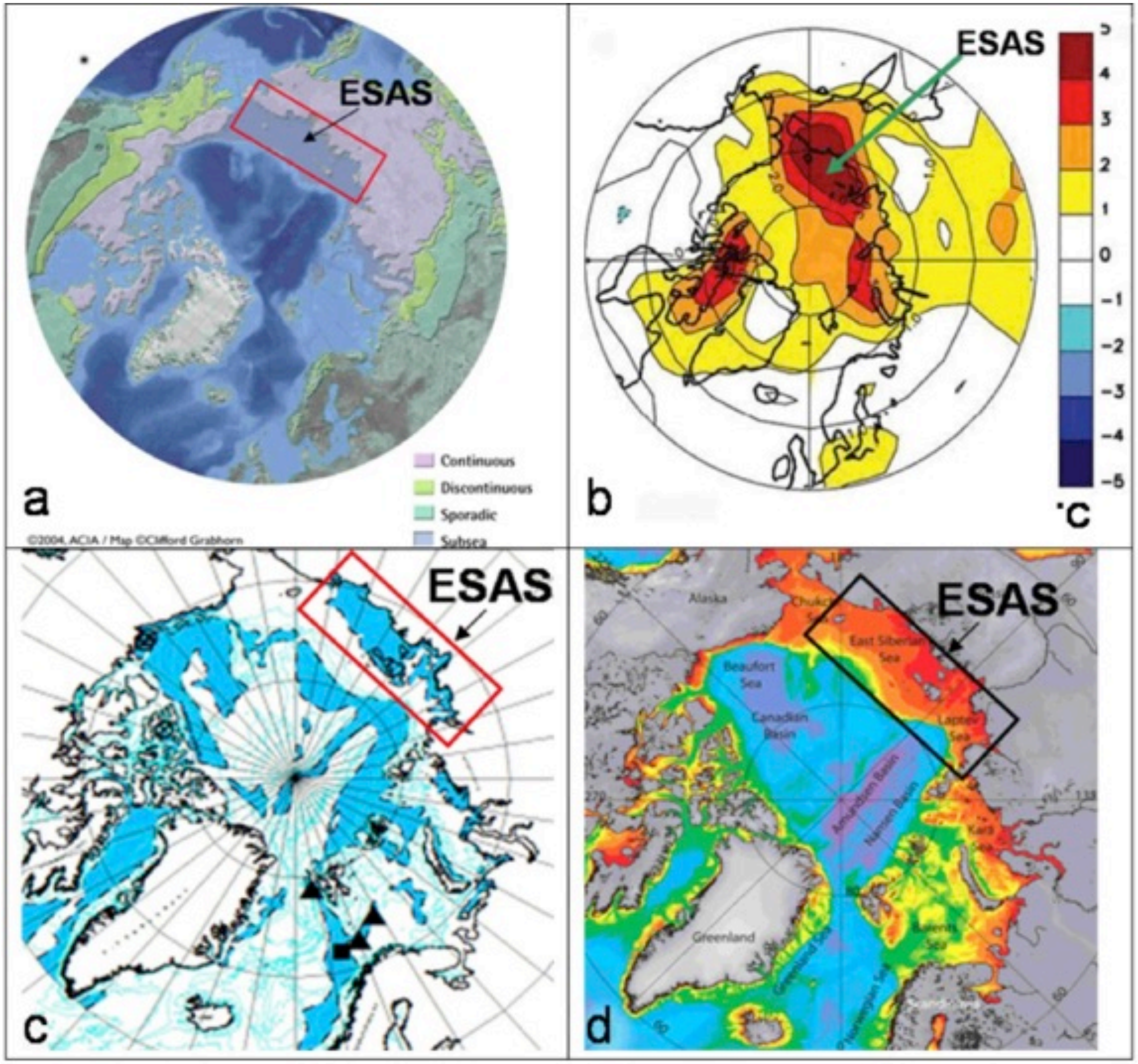
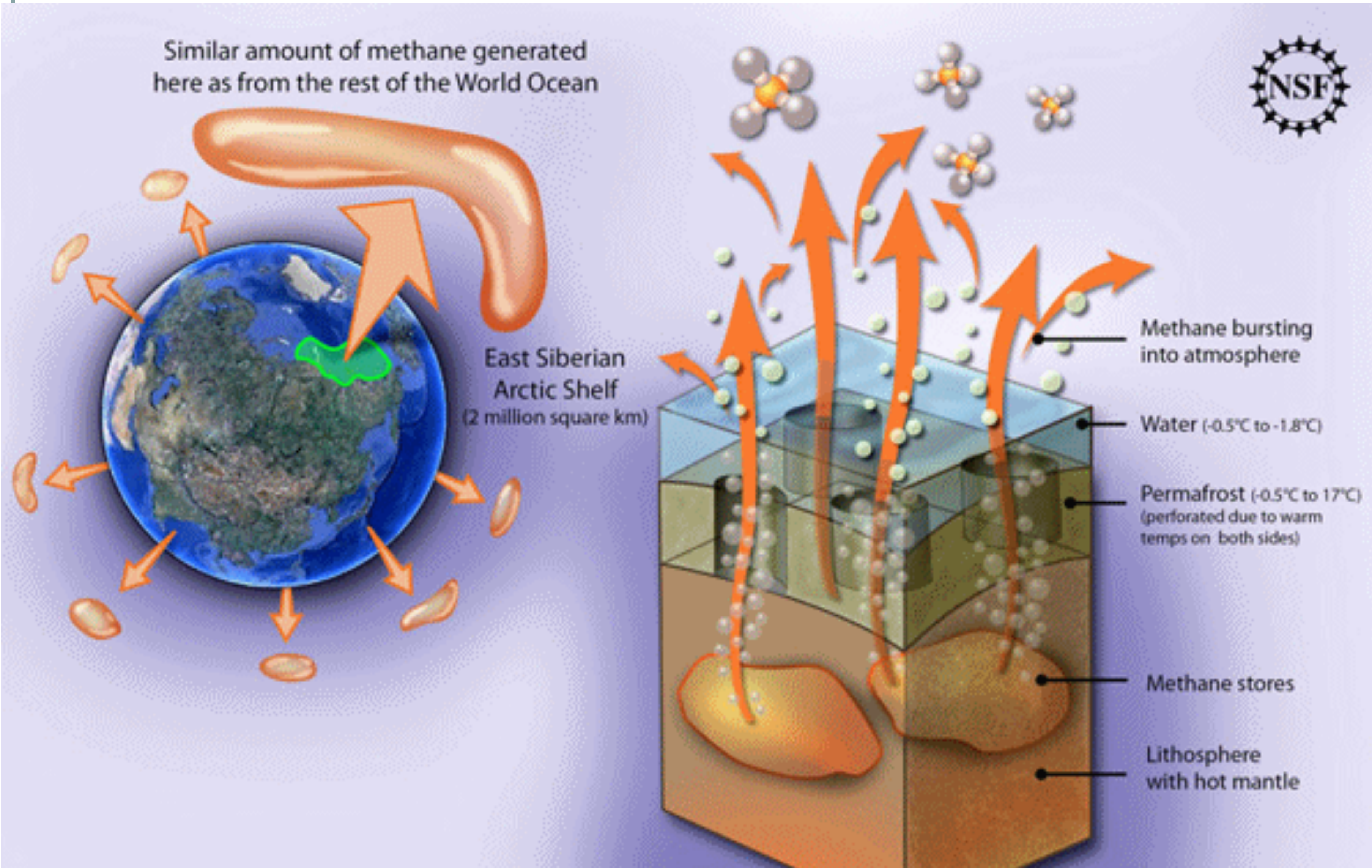


Figure 1. (a) Distribution of Arctic Ocean sub-sea permafrost (shown in purple); (b) springtime surface air temperature anomalies for 2000–5 relative to a 1968–96 base period; (c) predicted deposits of Arctic Ocean CH_4 hydrates (shown in blue); (d) bathymetric map of the Arctic Ocean (depth $\leq$ 50 m shown in shades of red) http://iopscience.iop.org/1748-9326/7/1/015201/article



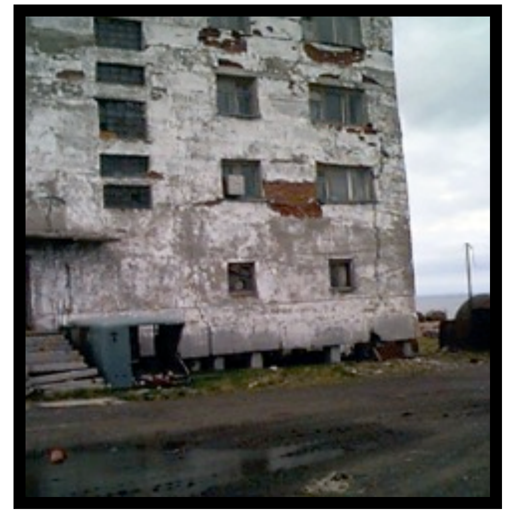
http://www.zeeburgnieuws.nl/nieuws/images/methane_hydrate_nsf.gif

Climate change headlines…

Are Siberia's methane blow-holes the first warning sign of unstoppable climate change?

Need to educate yourself about headlines like this and the underlying system.

Buildings affected by melting permafrost



Environmental Problems of Permafrost

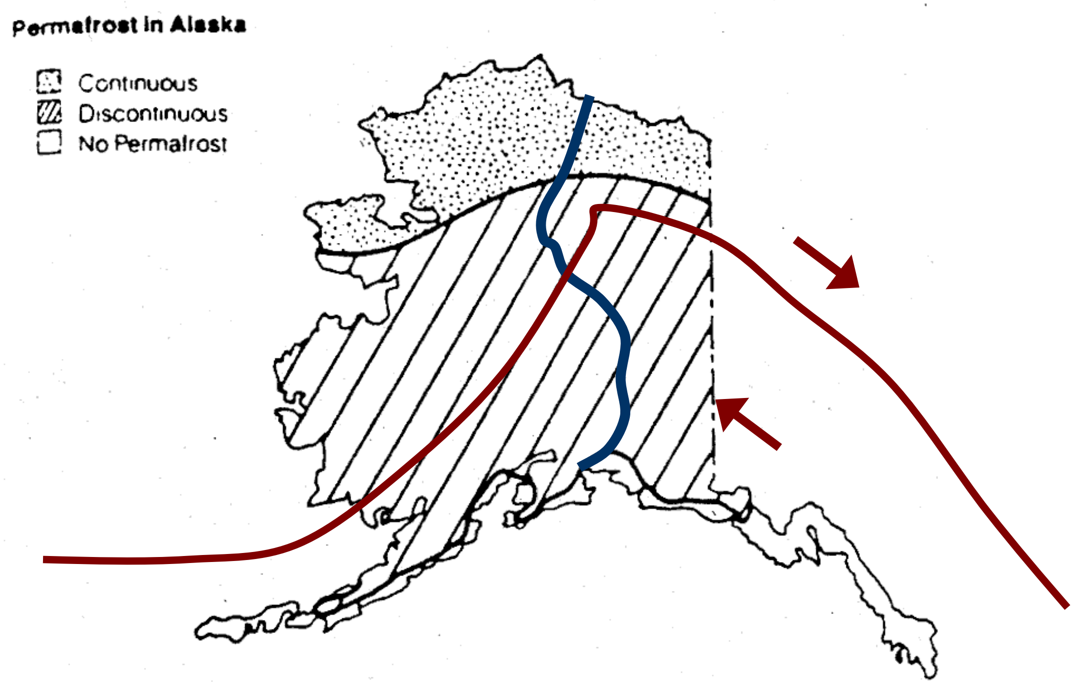
Human activities degrade the permafrost environment

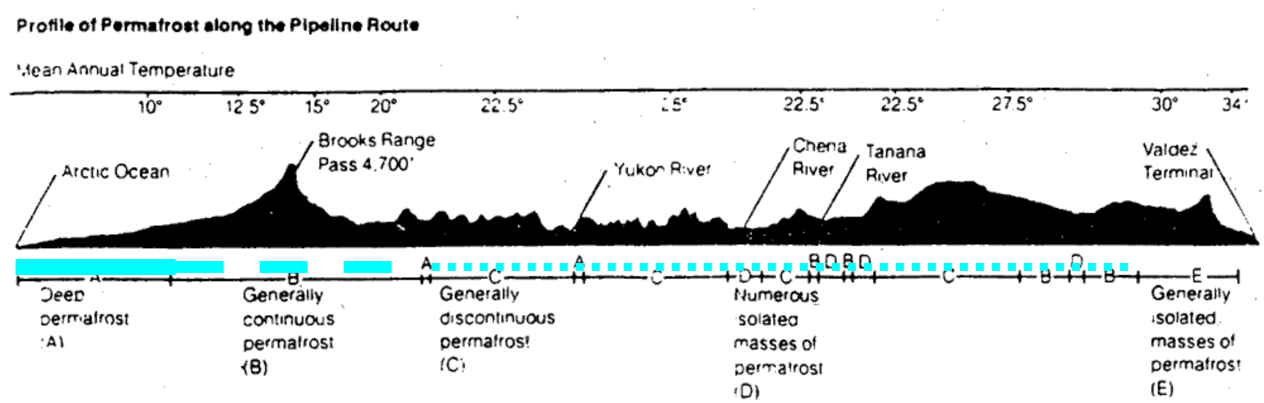
- *Thermal erosion*: surface layer removed, so the thaw extends deeper into the ground
- *Thermokarst*: natural surface removed over large areas of tundra leads to ground subsidence that results in depressions and lakes — ground may subside and buildings may collapse
- Buildings must be insulated
- Pipelines must be placed aboveground, for them not to thaw permafrost, or not to freeze

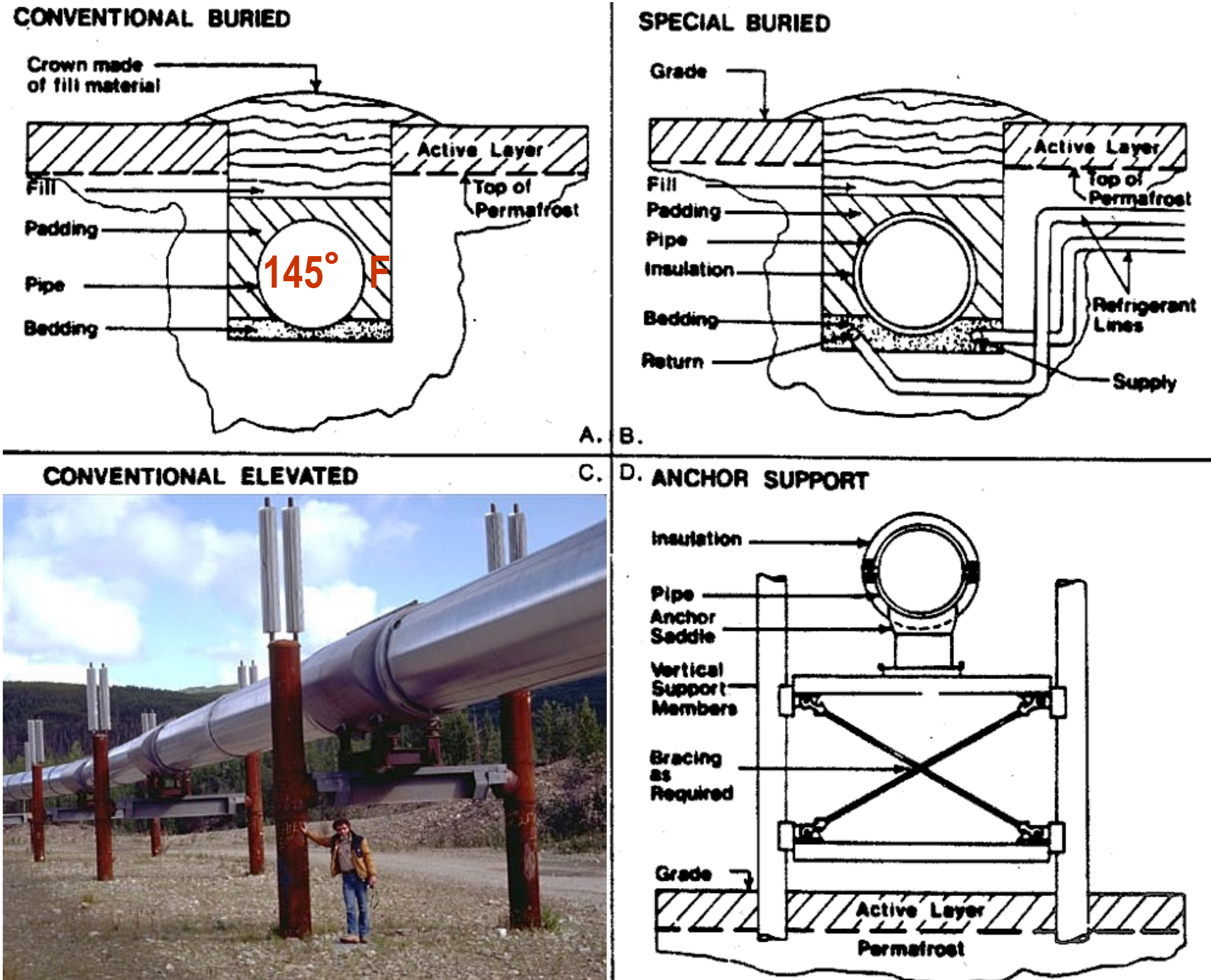
Alaska Pipeline: an engineering miracle instead of an environmental disaster

- Continuous and discontinuous permafrost regimes

- Active Tectonics






CONVENTIONAL BURIED
Crown made of fill material
Active Layer
Fill
Top of Permafrost
Padding
145° F
Pipe
Bedding
A.
SPECIAL BURIED
Grade
Active Layer
Fill
Top of Permafrost
Padding
Pipe
Insulation
Refrigerant Lines
Bedding
Return
Supply
B.
CONVENTIONAL ELEVATED
C.
D. ANCHOR SUPPORT
Insulation
Pipe
Anchor Saddle
Vertical Support Members
Bracing as Required
Grade
Active Layer
Permafrost

Trans-Alaskan Pipeline

Astonishing engineering success instead of environmental catastrophe

- Oil transport
  - emerges from the ground at 180 ° F (80 ° C)
  - flows in pipeline at temperatures above 120 ° F

- VSM's (vertical support members)
  - Equipped with heat exchangers to prevent warming of ground material
  - Allow the pipeline to efficiently transfer oil without affecting stability
  - Allows wildlife to maintain migratory patterns

Lots of ice below the surface in the Arctic

Freezing Clay: Ice lenses (Tabor)

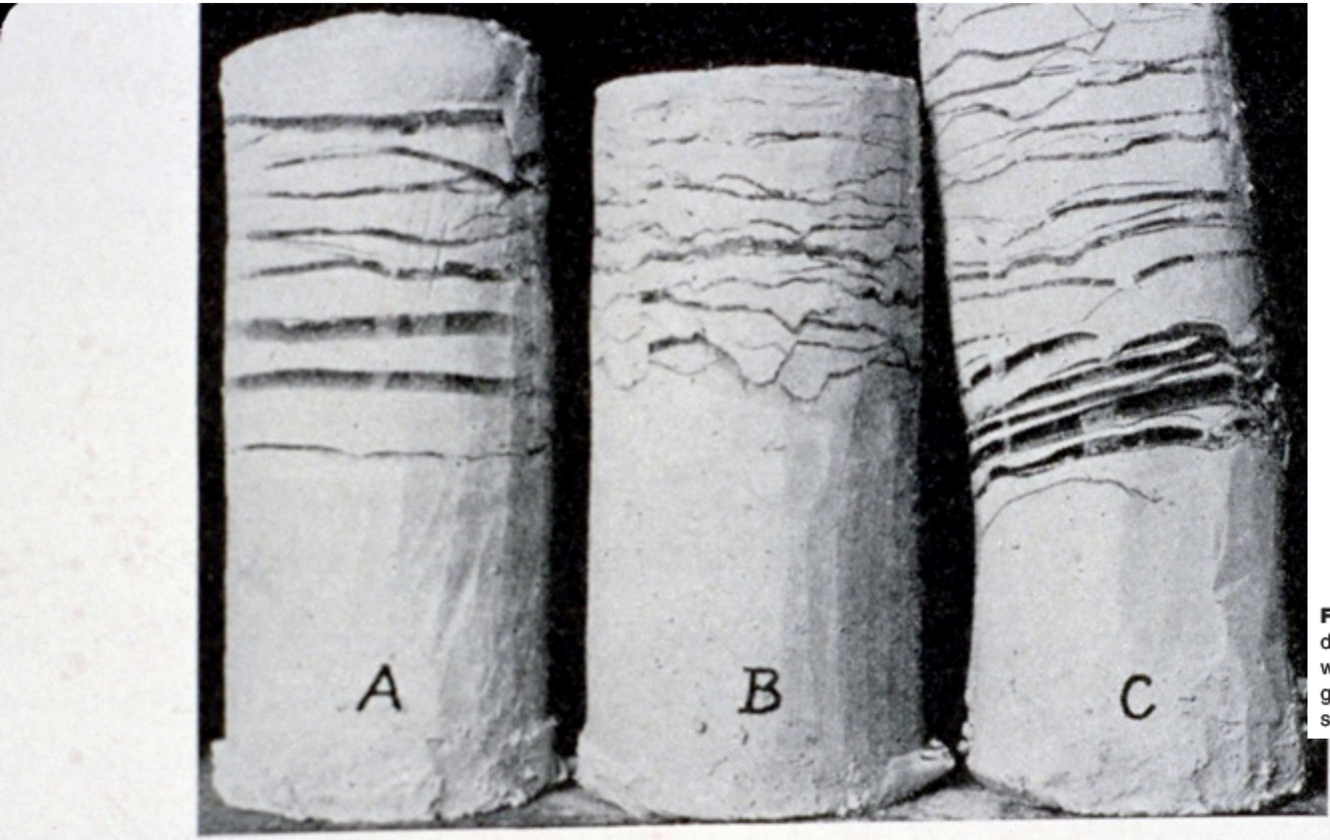


FIG. 11.—Clay cylinders frozen (*A*) under no surface load; (*B*) under iron weigh[t in-]
sulated from clay by wooden disc; and (*C*) under iron weight in contact with clay.

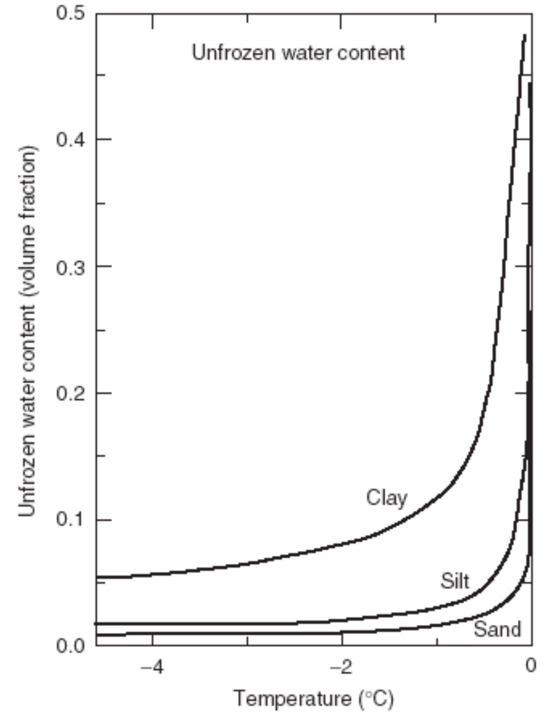
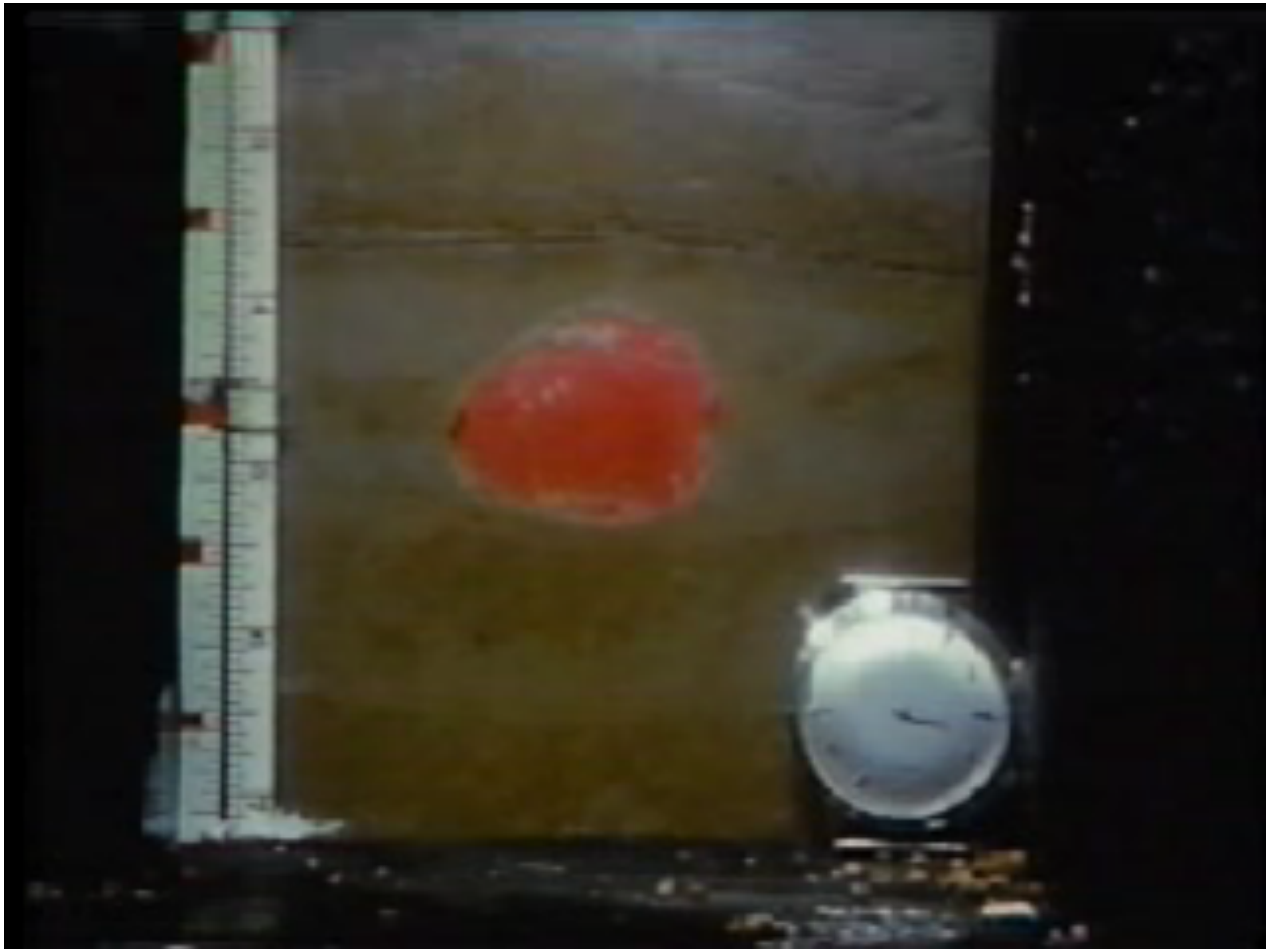


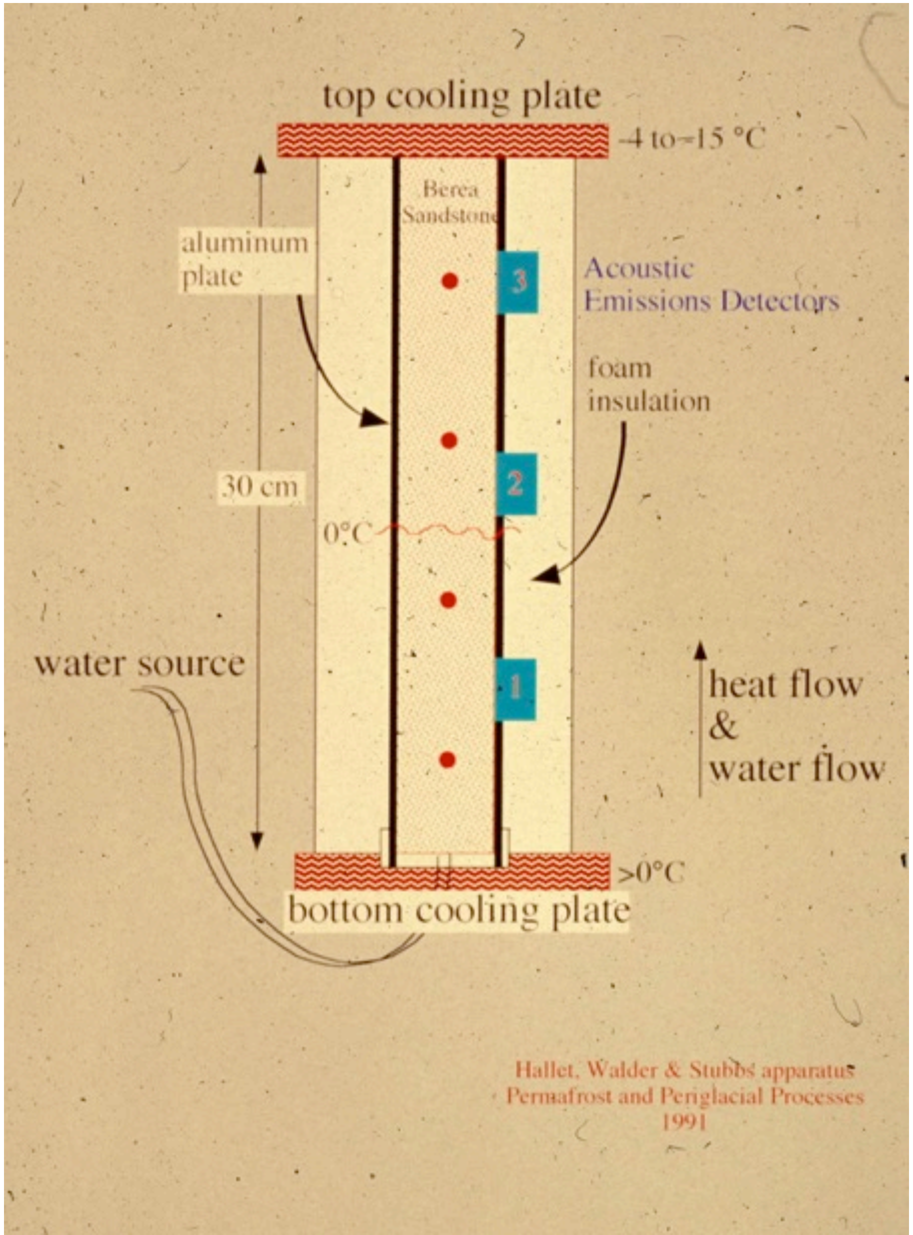
Figure 4 Representative values for the temperature dependence of unfrozen water contents in sand, silt, and clay. Unfrozen water contents typically increase with temperature and finer-grained soil and are small in moss and peat. The presence of solutes increases unfrozen water contents.

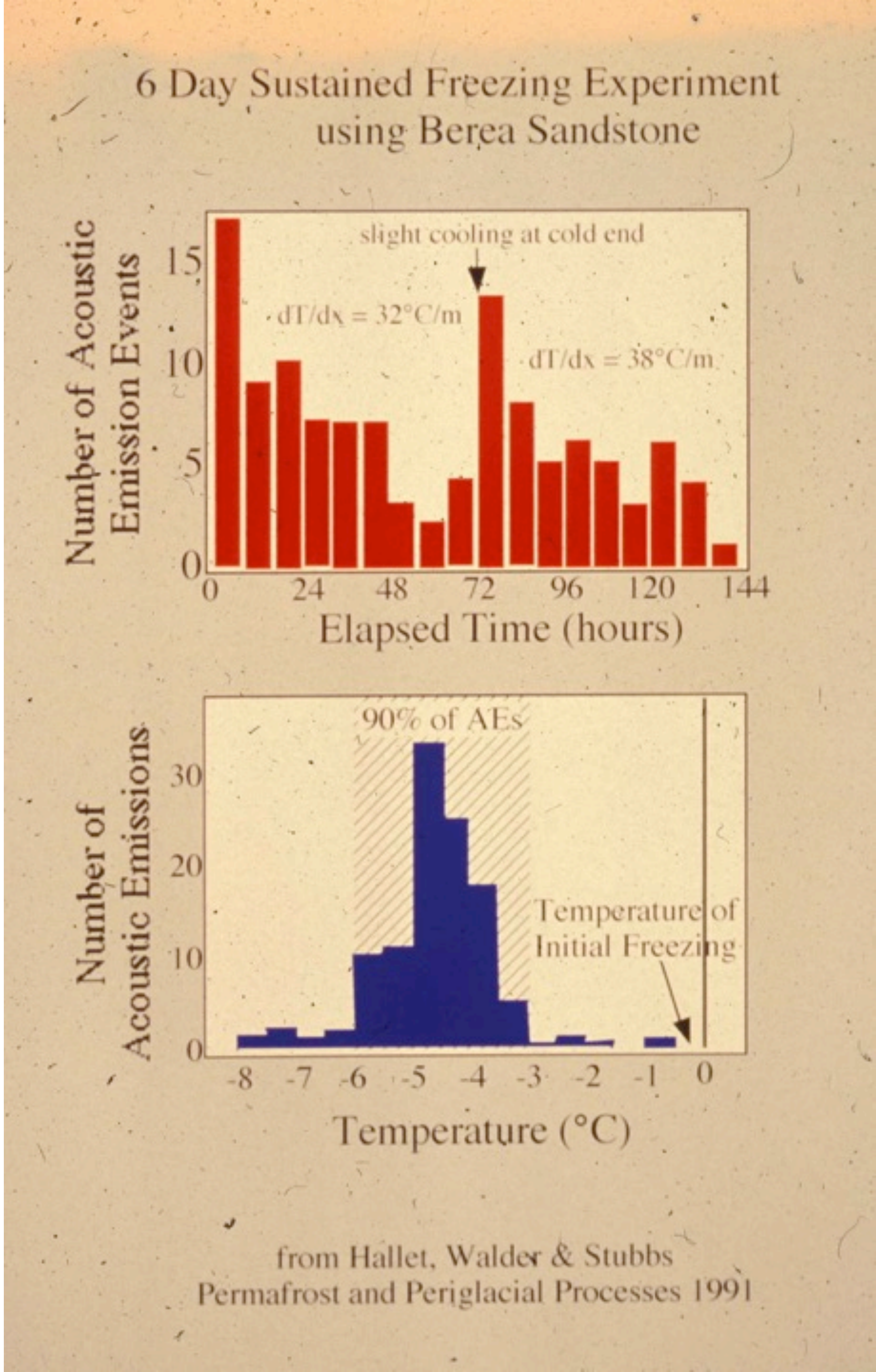


Cold Regions Res. & Eng. Lab (CRREL) movie of ~1-inch rock in freezing silt
About 3 days of freezing from the surface down in ~1 minute
Kaplar, C.W.,1976. Stone migration by freezing of soil [In :King, C.A.M. (Ed.), Periglacial processes . Stroudsburg, PA, Dowden, Hutchinson & Ross, Inc., pp. 44–45.]

Freezing is also very effective in breaking down rock, but why?

Lab test of theory…





"The strange beauty of ice extruded from the earth on a cold morning contains hidden secrets of nature for those who look beneath their feet."

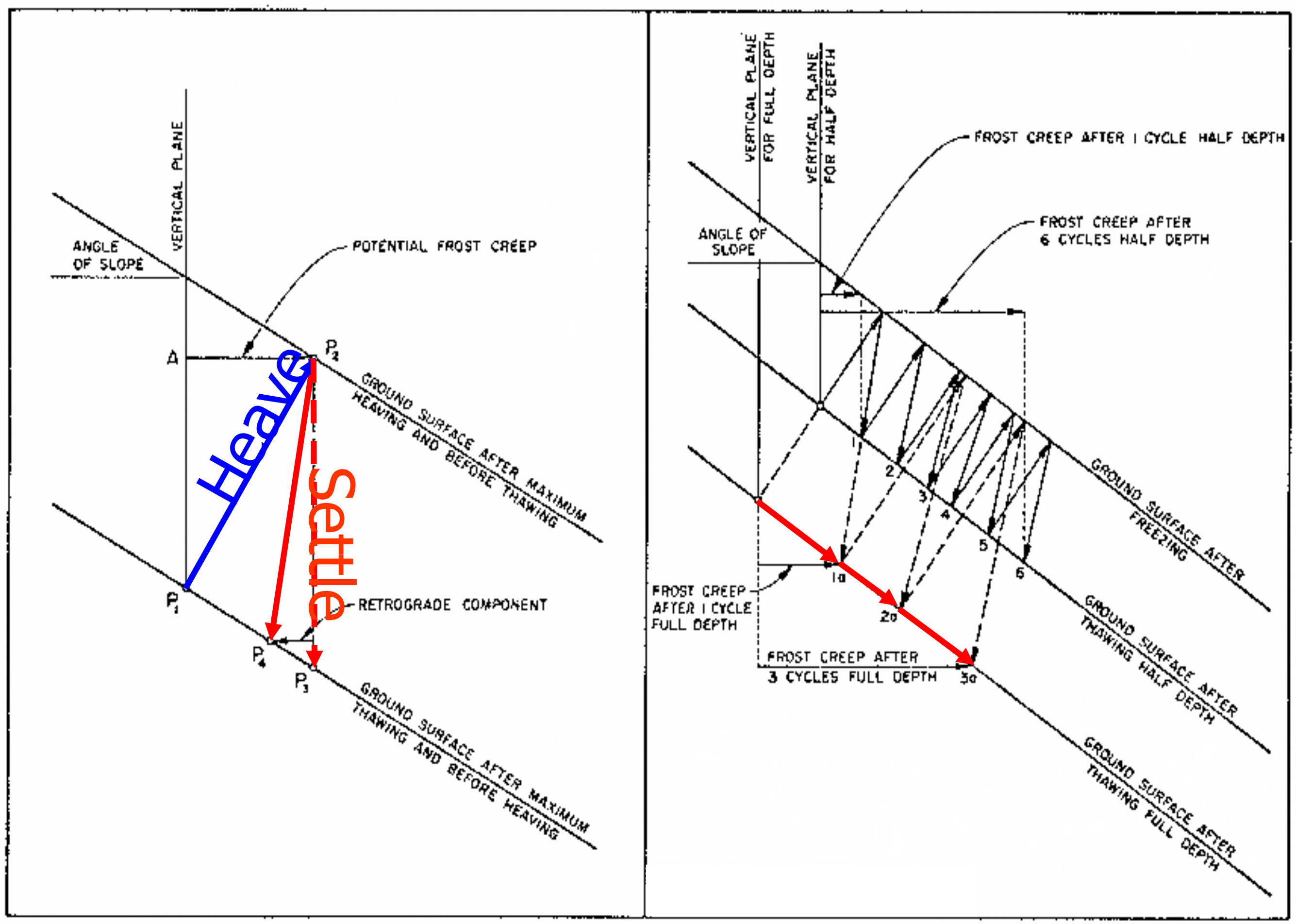
by David Cavagnaro
This Living Earth

Needle Ice, Sierra Nevada

Frost Heave

- Heave
  - Moisture
  - Grain size

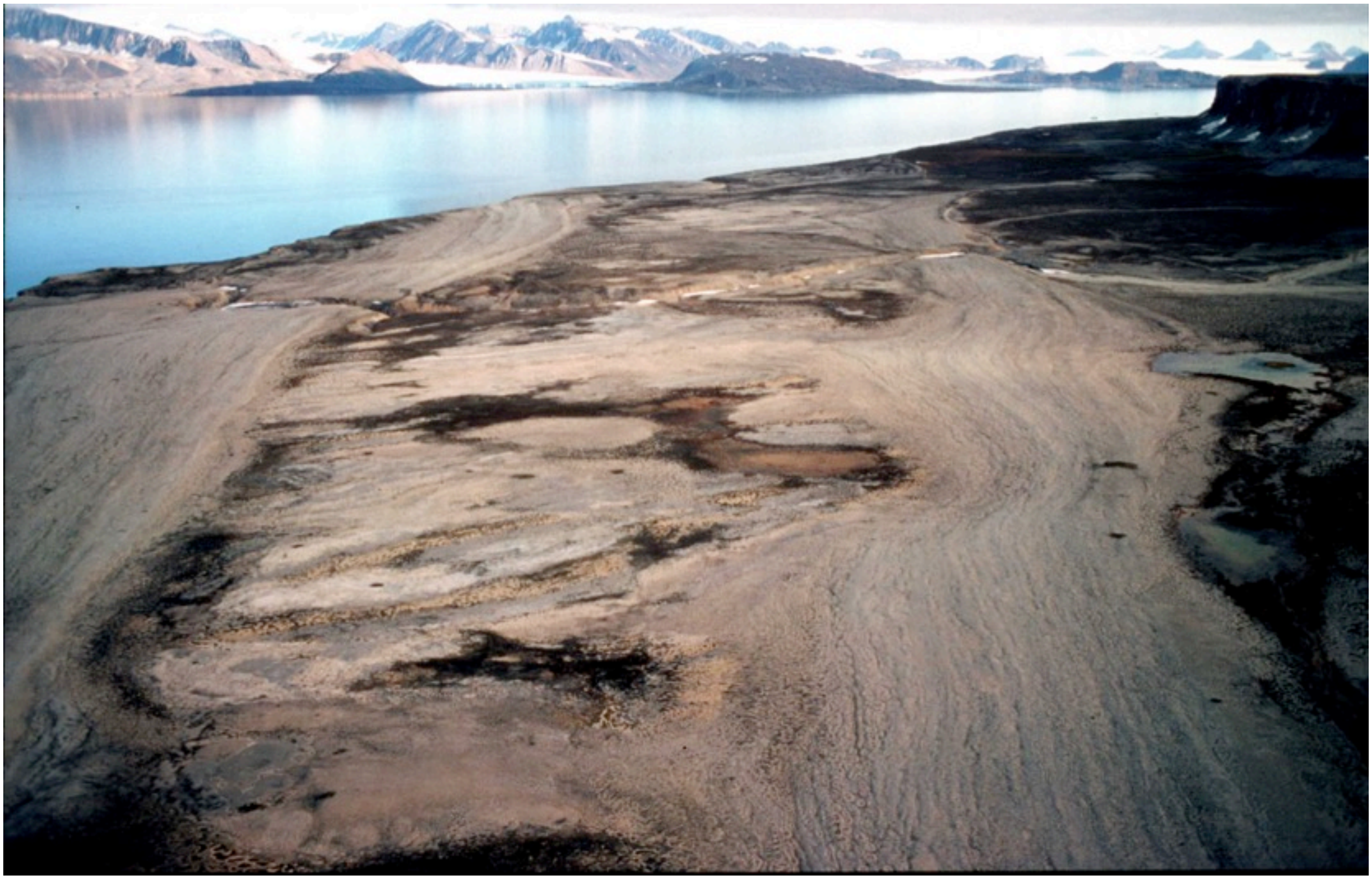
- Creep
  - Saturation
  - Grain size
  - Slope



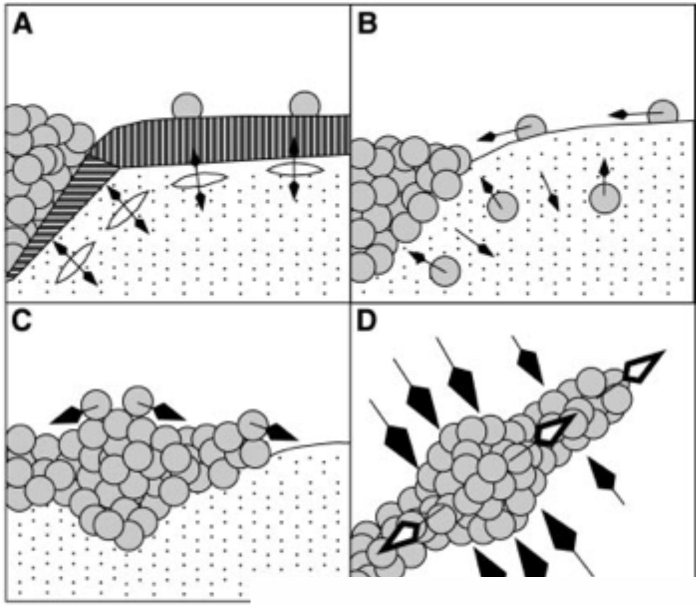
Subsurface ice growth & melt creates patterns in Hawaii: Sorted stripes, Mauna Kea

An intriguing product of seasonal freeze/thaw on raised beaches, Spitsbergen

Isostatic Uplift due to reduced ice load

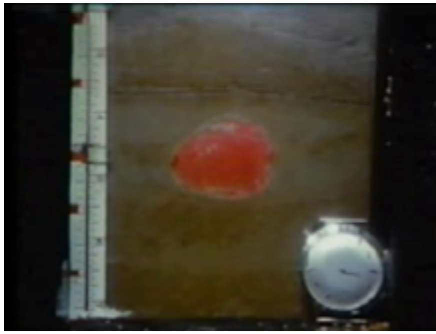


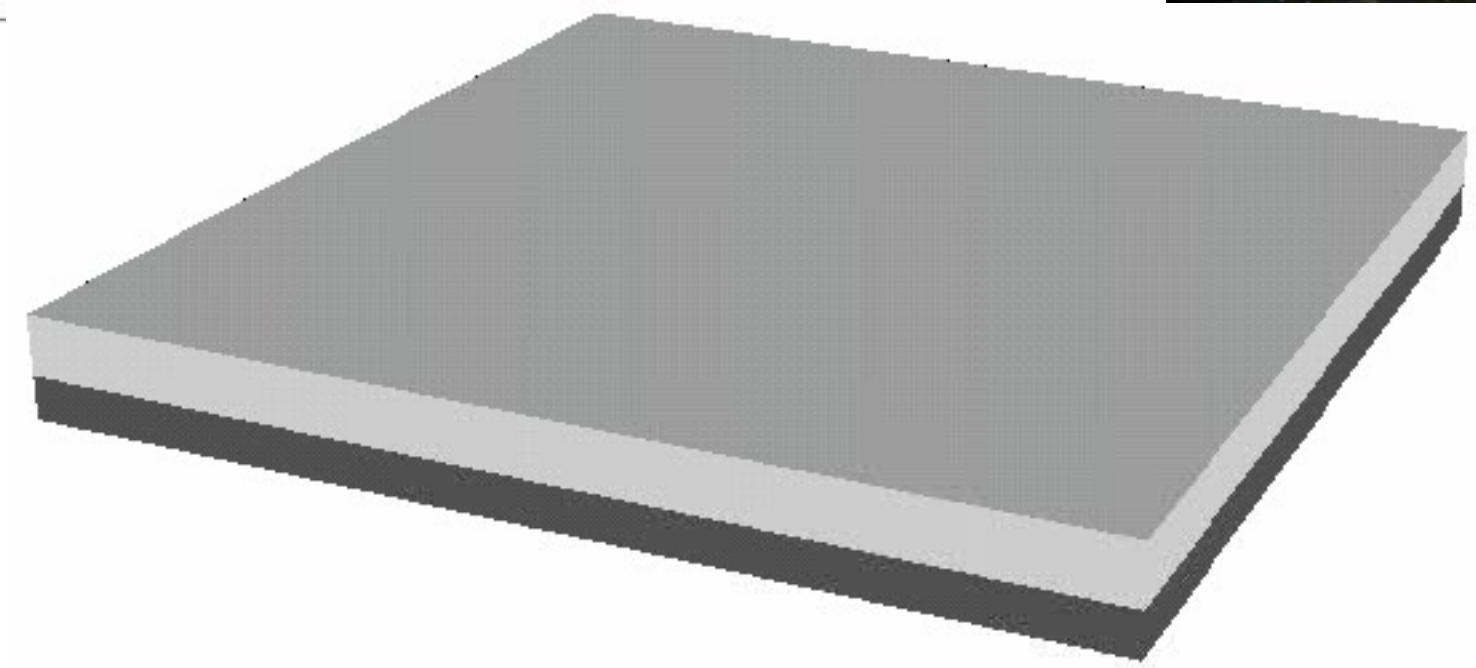
Stone Circles, Spitsbergen



Mark Kessler's Model
4 simple elements

A. Texture impacts freezing front
B. Frost sorting of stones
C. Downslope creep
D. Lateral pressure

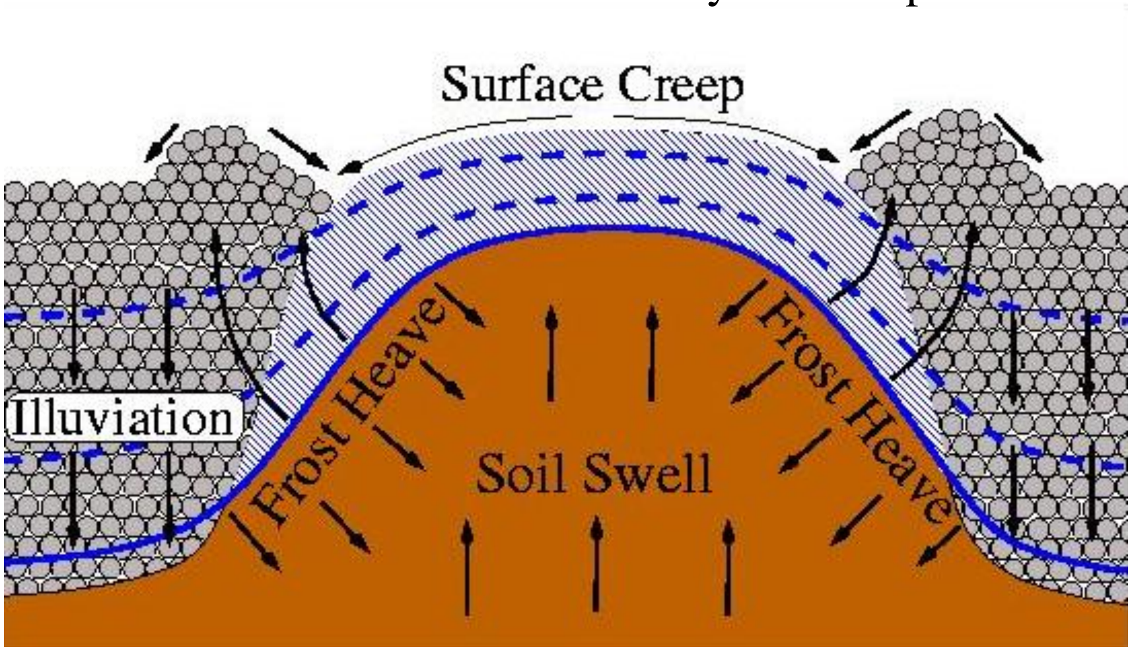




Patterns: hallmark of complexity

Soil diapirs form due to recurrent freeze-thaw cycles

Original state: layer of mixed material of nearly uniform thickness
Initial Phase: larger stones/pebbles move to the surface (upfreezing)
and then move laterally downslope



Courtesy of
Mark Kessler

Numerical model is consistent with conceptual model based on field observations

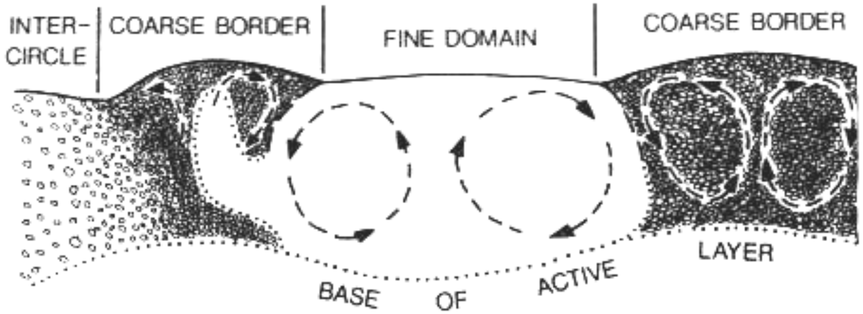


Fig. 5. Movements in sorted circles proposed by Hallet et al. (1988).

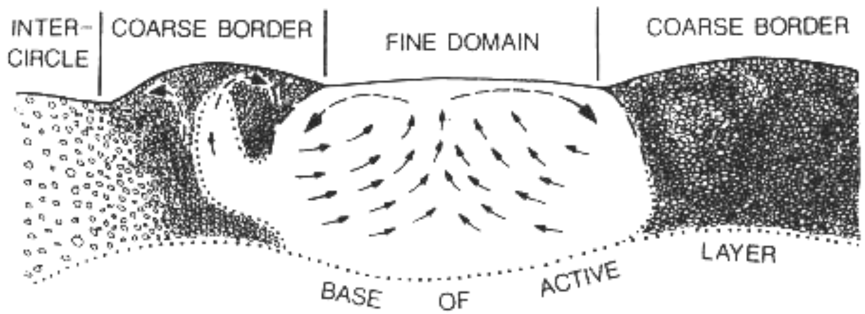


Fig. 6. Another possible explanation of the movements observed on the surface by Hallet et al. (1988).

Cryoturbation: broader importance

It impacts cycling of soil carbon and release of carbon from permafrost to the atmosphere

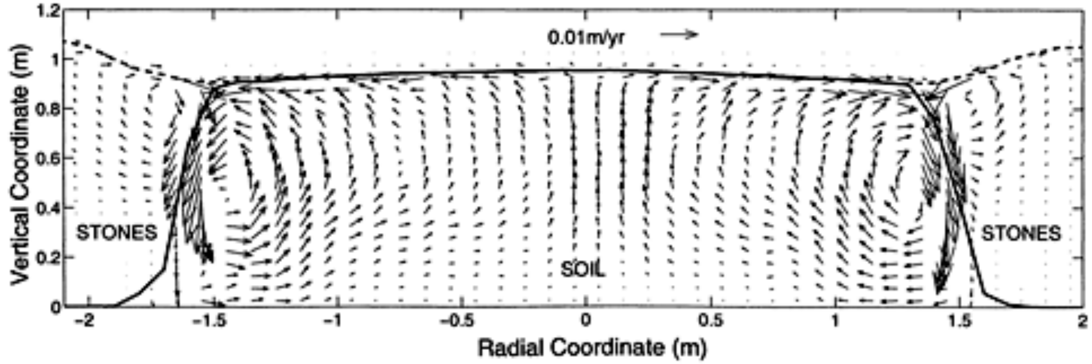
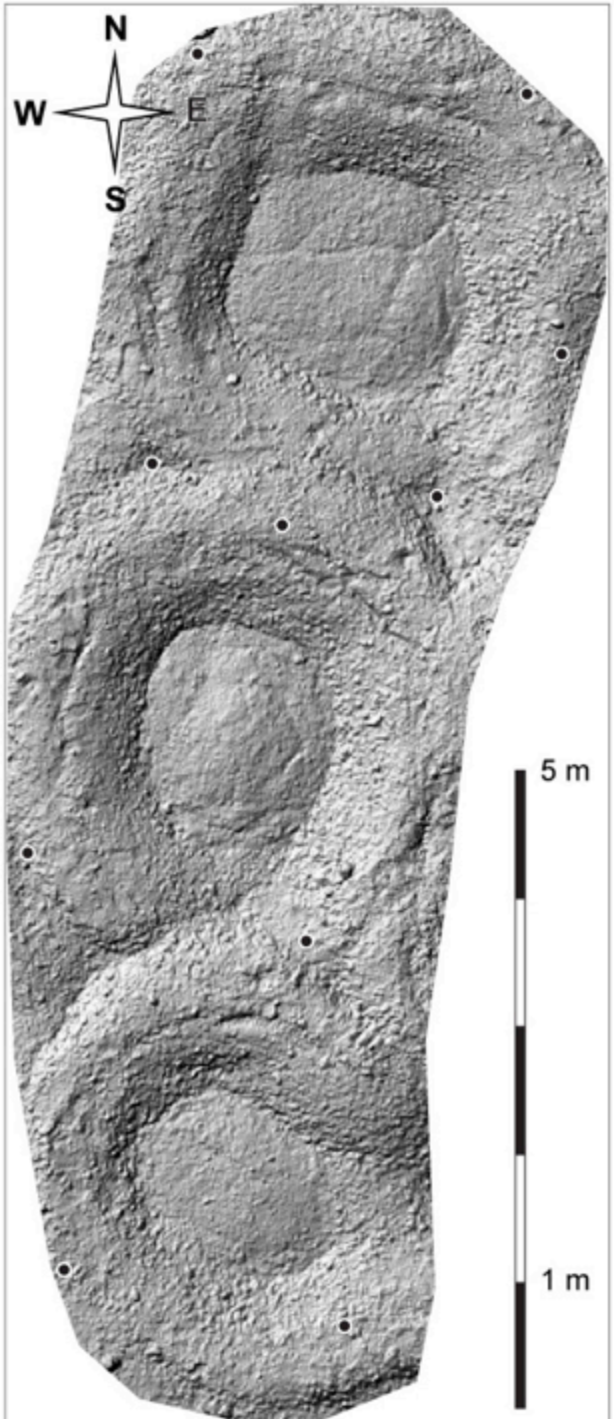
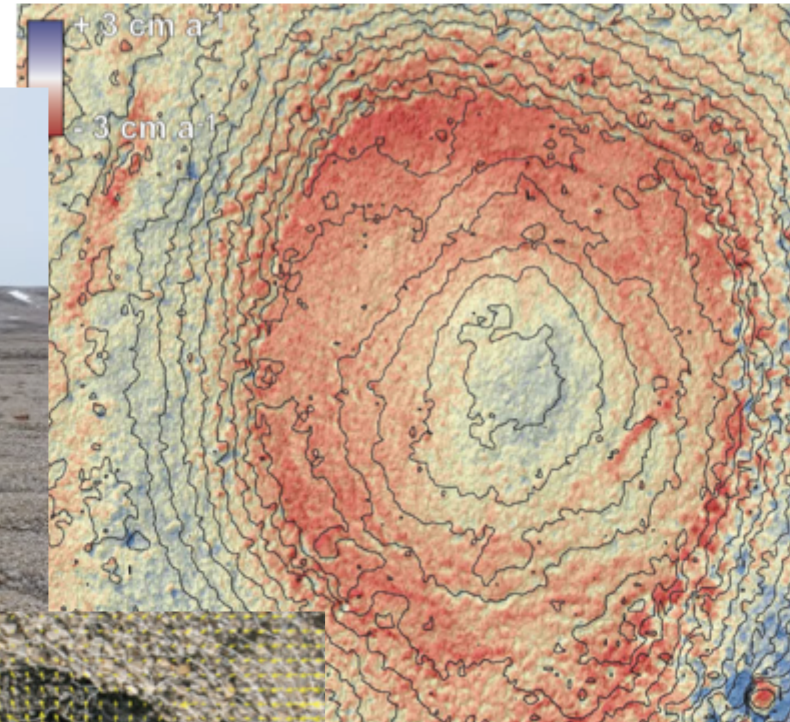


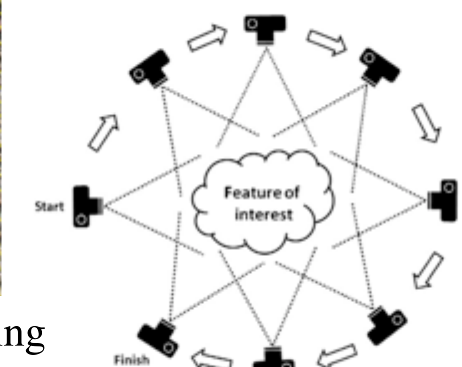
Figure 9. Velocity vectors in a cross section of a well-developed sorted circle from the reference model, as in Figure 8. Solid line is the soil surface; dashed line is the ground surface.

Exciting emerging technology (software & hardware) http://www.the-cryosphere.net/8/1041/2014/tc-8-1041-2014.pdf



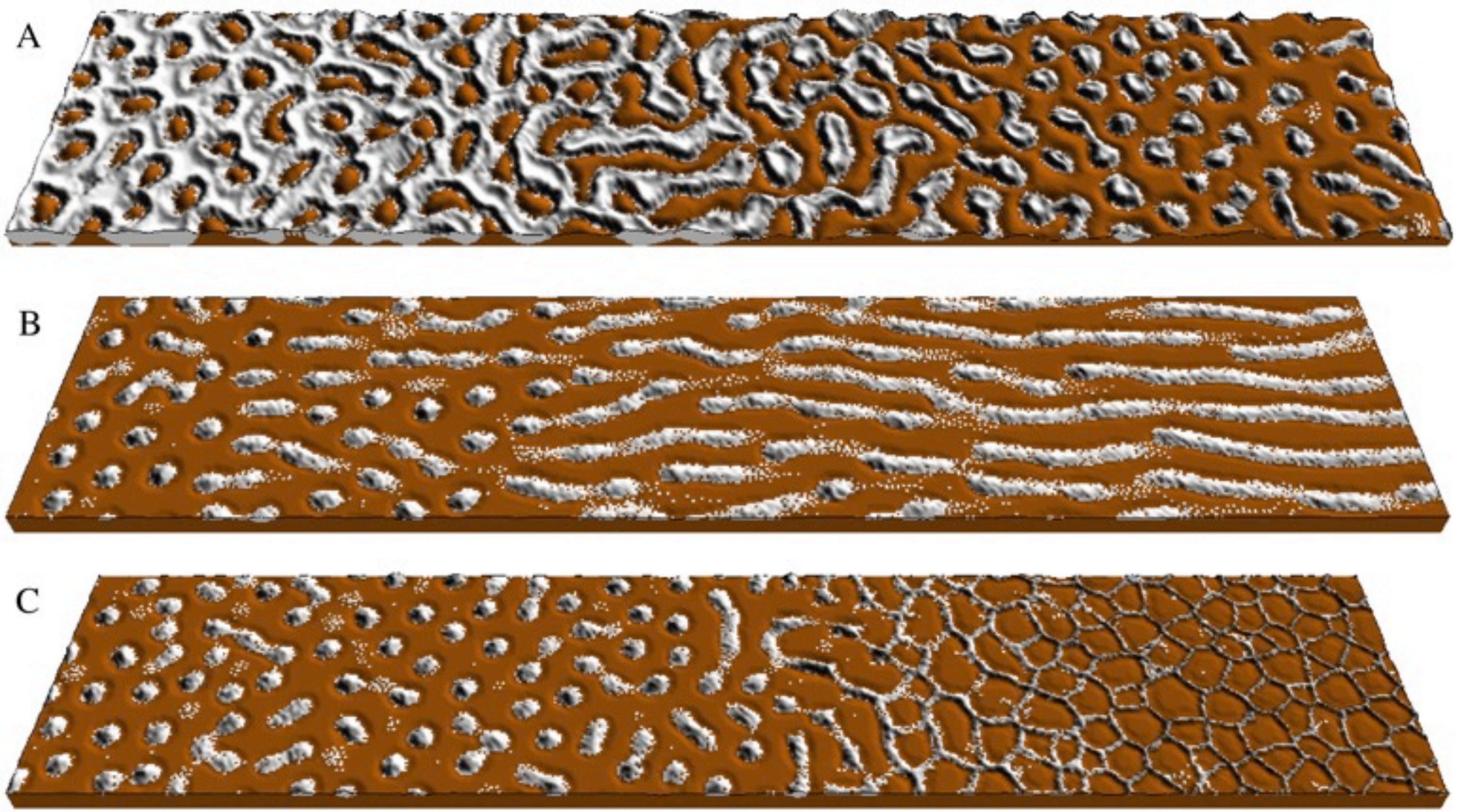


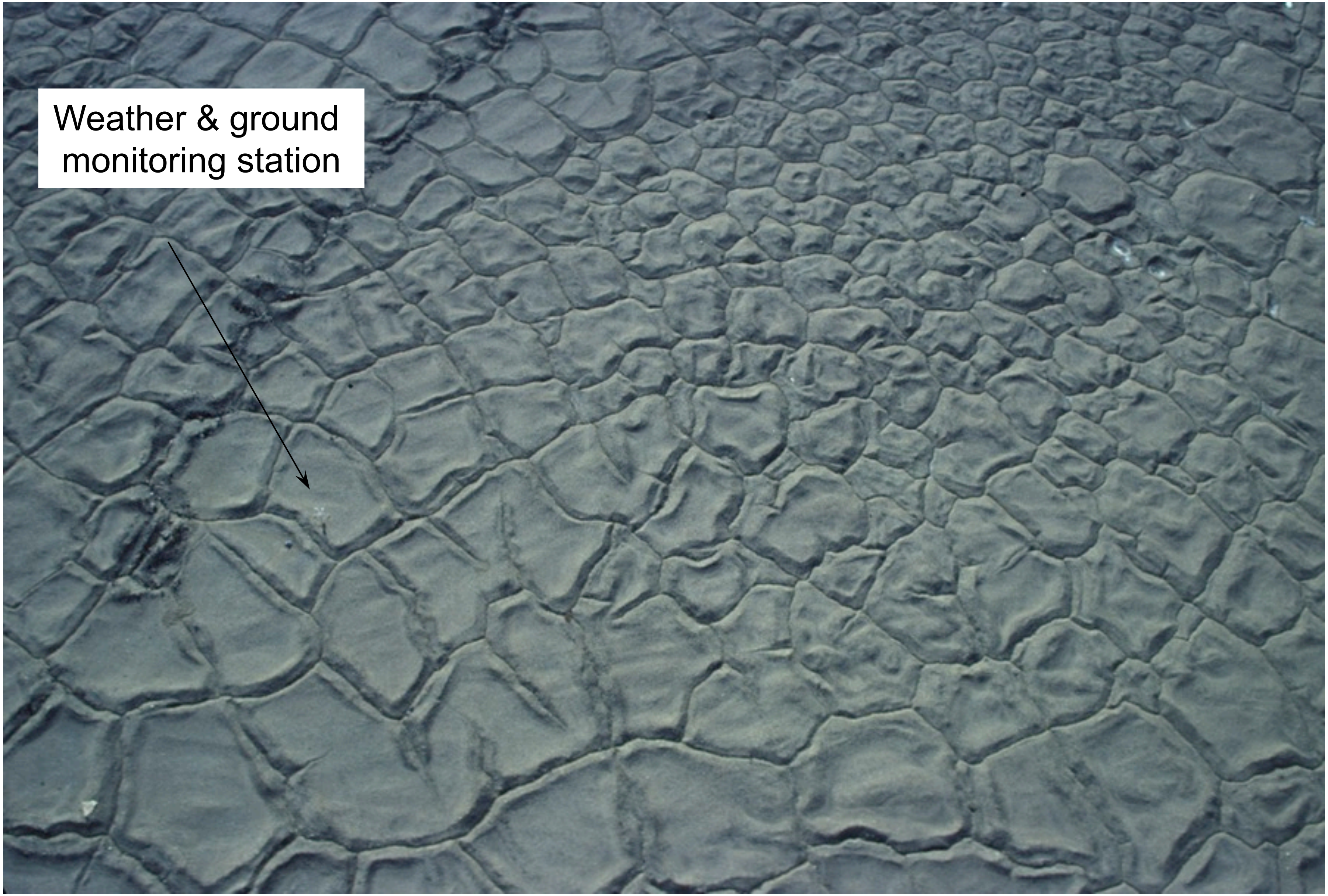
Kaab et al., 2014



Structure from Motion (SfM), using cameras from ladders, satellites & drones

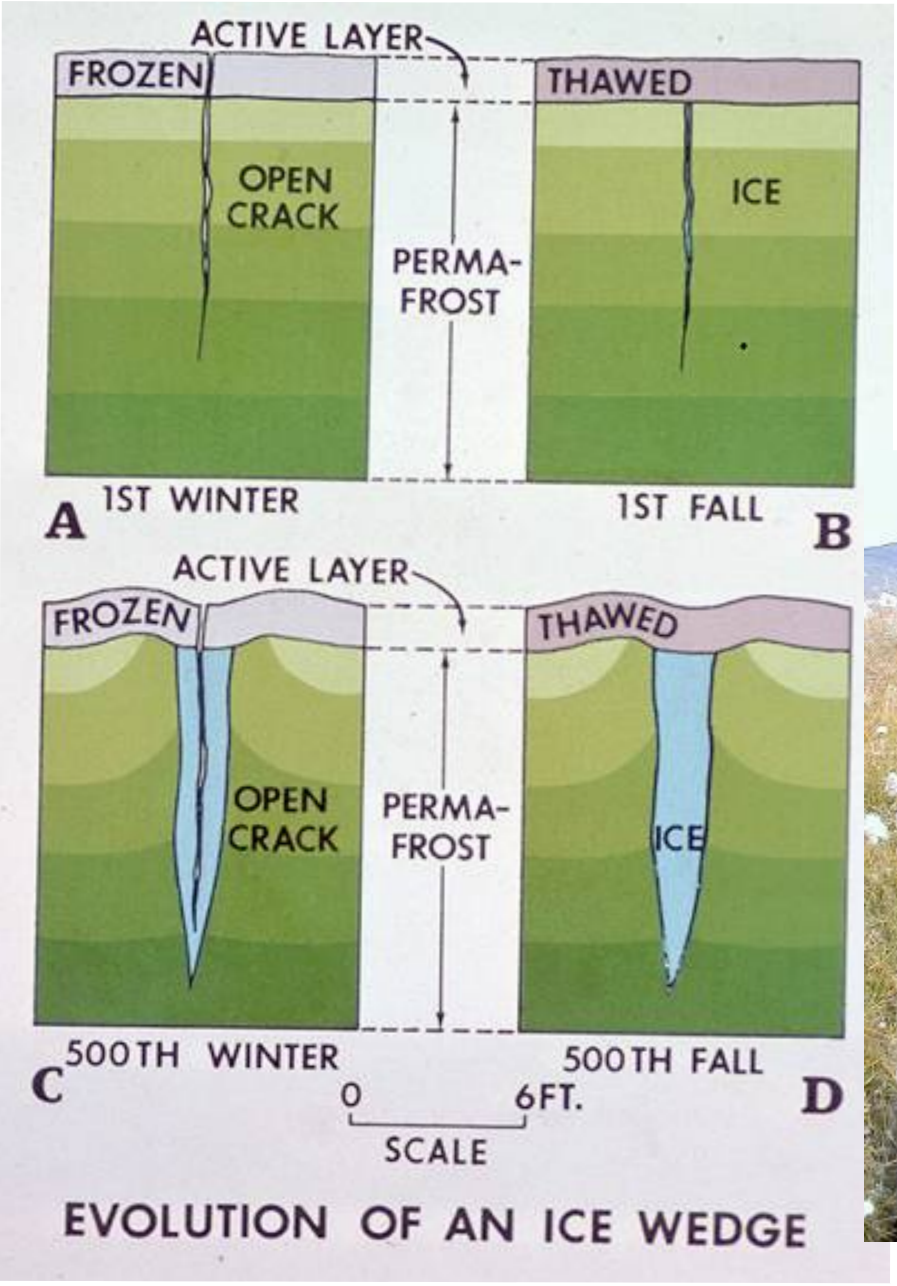
Kessler and Werner's model produce rich and realistic diversity of patterns

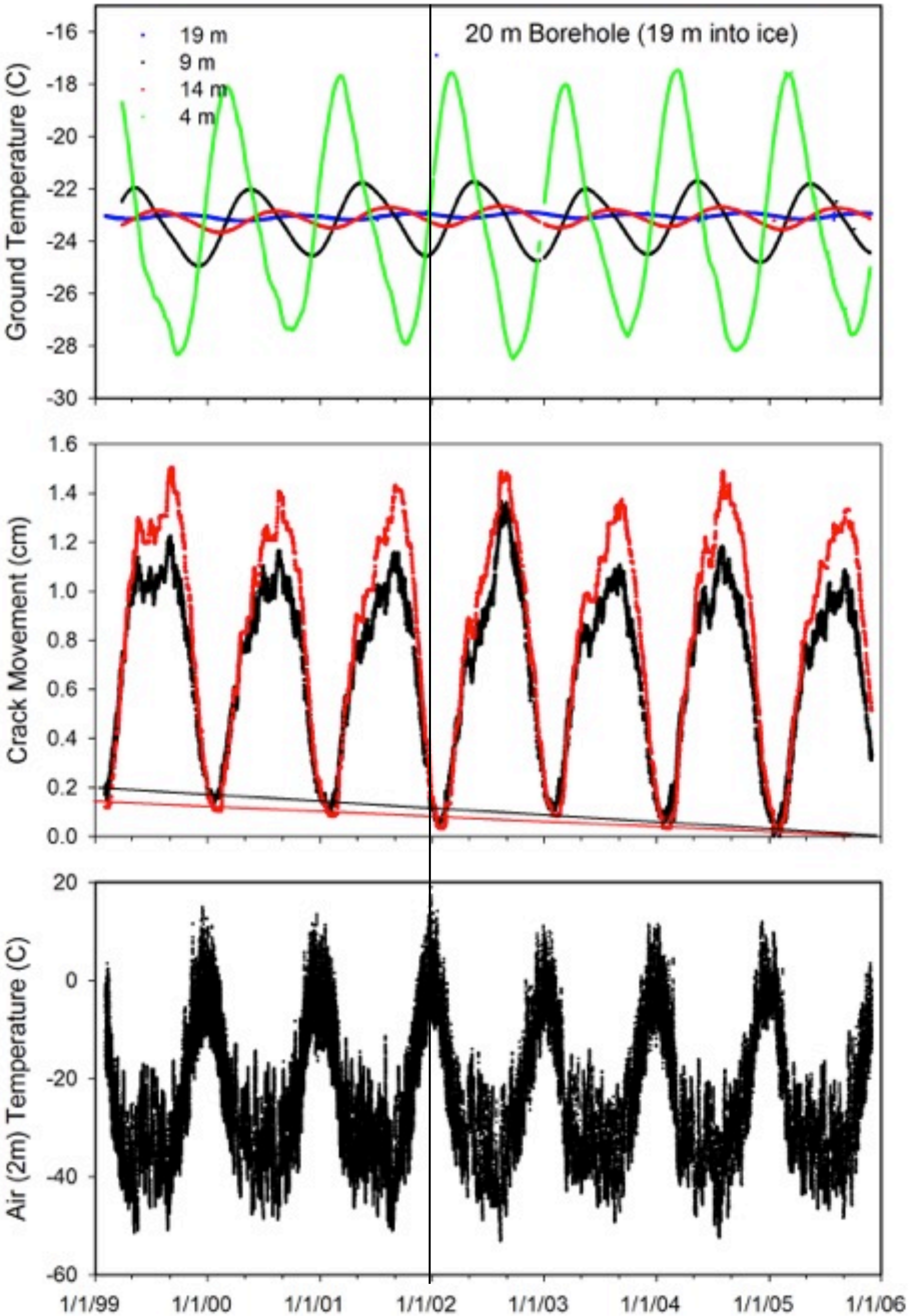



Weather & ground
monitoring station

Ice-Wedge Polygons

Spacing is a small multiple of crack depth





Summary for Central Beacon Valley; Underlain by massive ice

•Temperature variations diminish with depth and lag the surface signal

•Seasonal "breathing": Greatest annual contraction/expansion

•No sustained divergence across crack

Rapid Soil Creep (Solifluction) Lobes

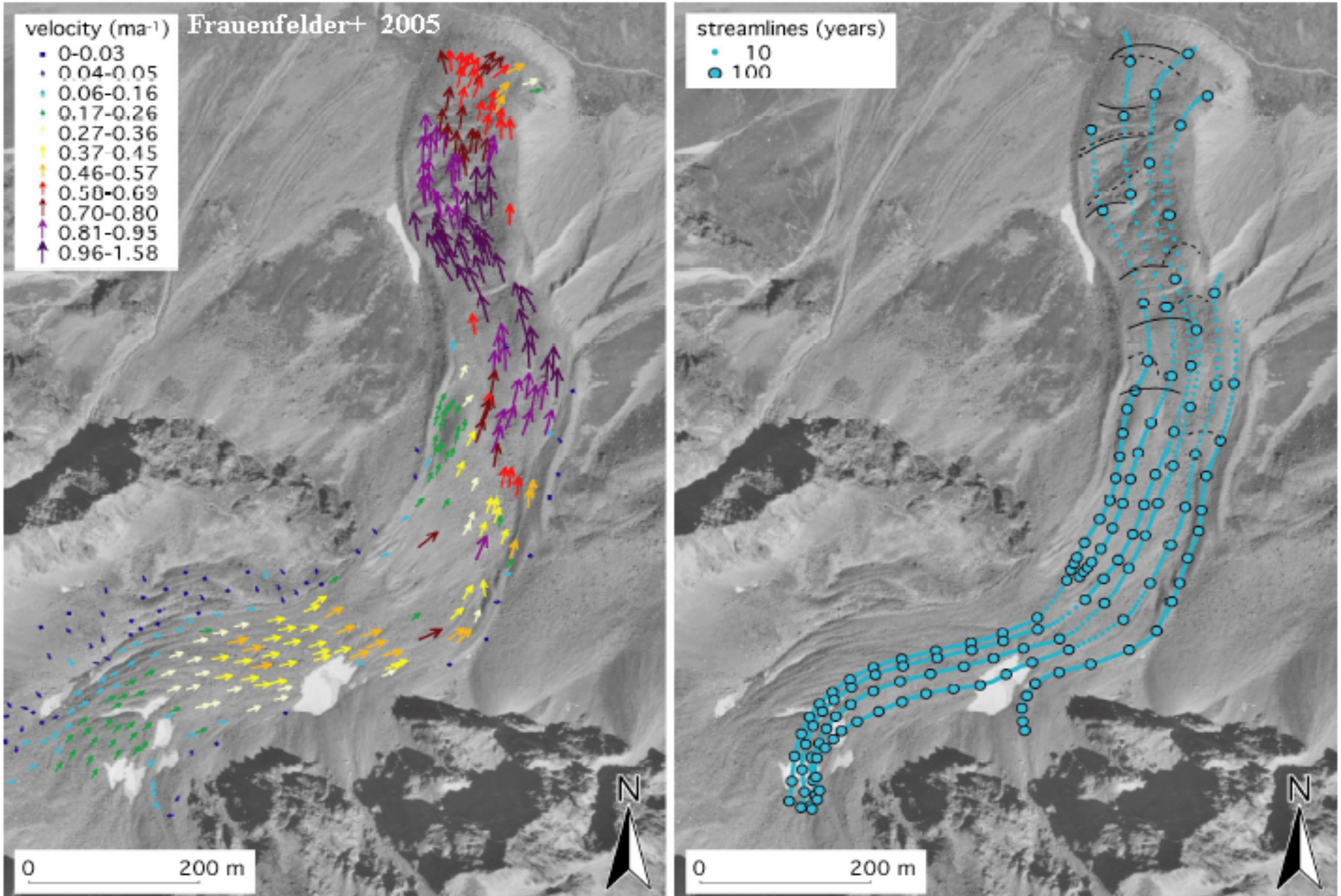
Rock Glacier
S. Alaska

http://ngm.nationalgeographic.com/2007/12/permafrost/edmaler-photography.html

Mountain Permafrost: Glacial & periglacial processes

Ice-sculpted peaks and deep valleys filled with ice-debris mixtures (permafrost) in Peruvian Andes. Glacier perched on debris, and turquoise lakes. Why that color?

Rock Glacier



Back to the Arctic

Pingos

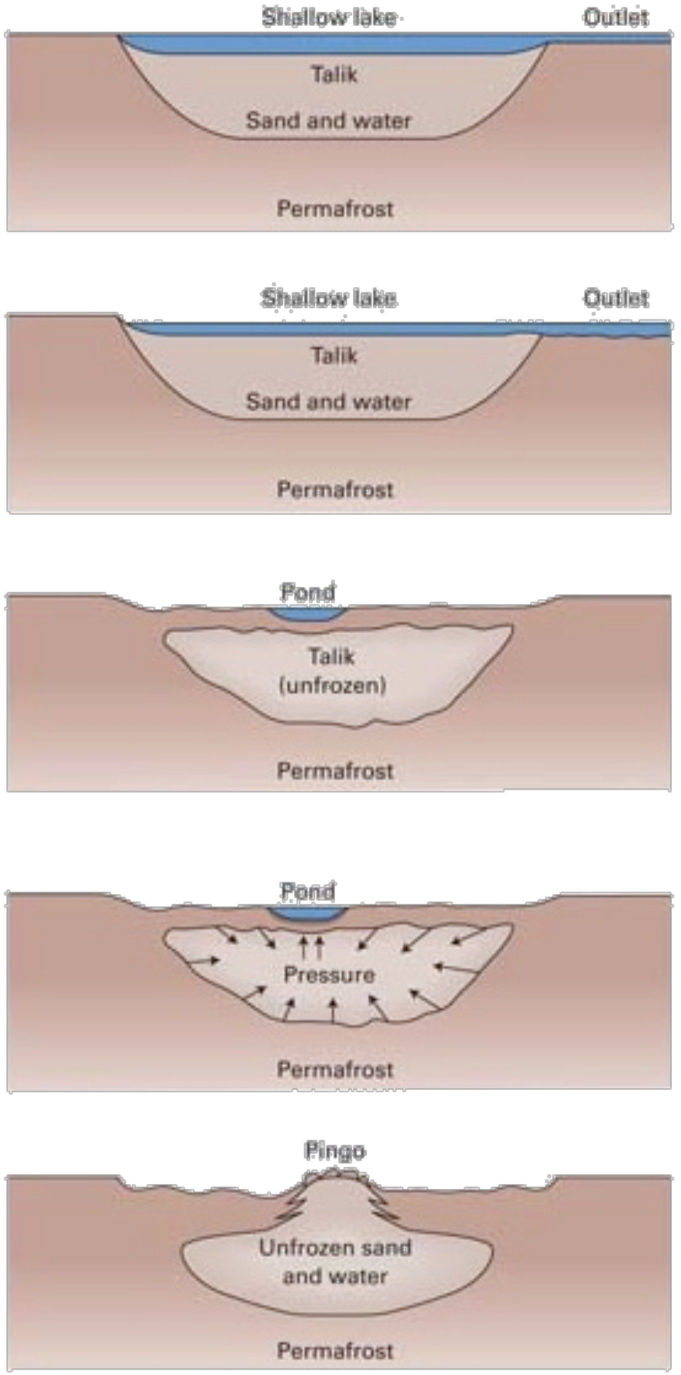
Conspicuous conical mound or circular hill, with a core of ice, found on tundra where permafrost is present.

Form under initially unfrozen lakes (taliks).

Pingos

If the lake is infilled with sediment and vegetation, or drained by drainage capture the insulation of the ground surface will increase and permafrost will advance from the sides and bottom of the talik - forcing water up into a zone of refreezing.

Growth of this “pingo ice” pops the overlying sediment up and results in an ice-cored hill.



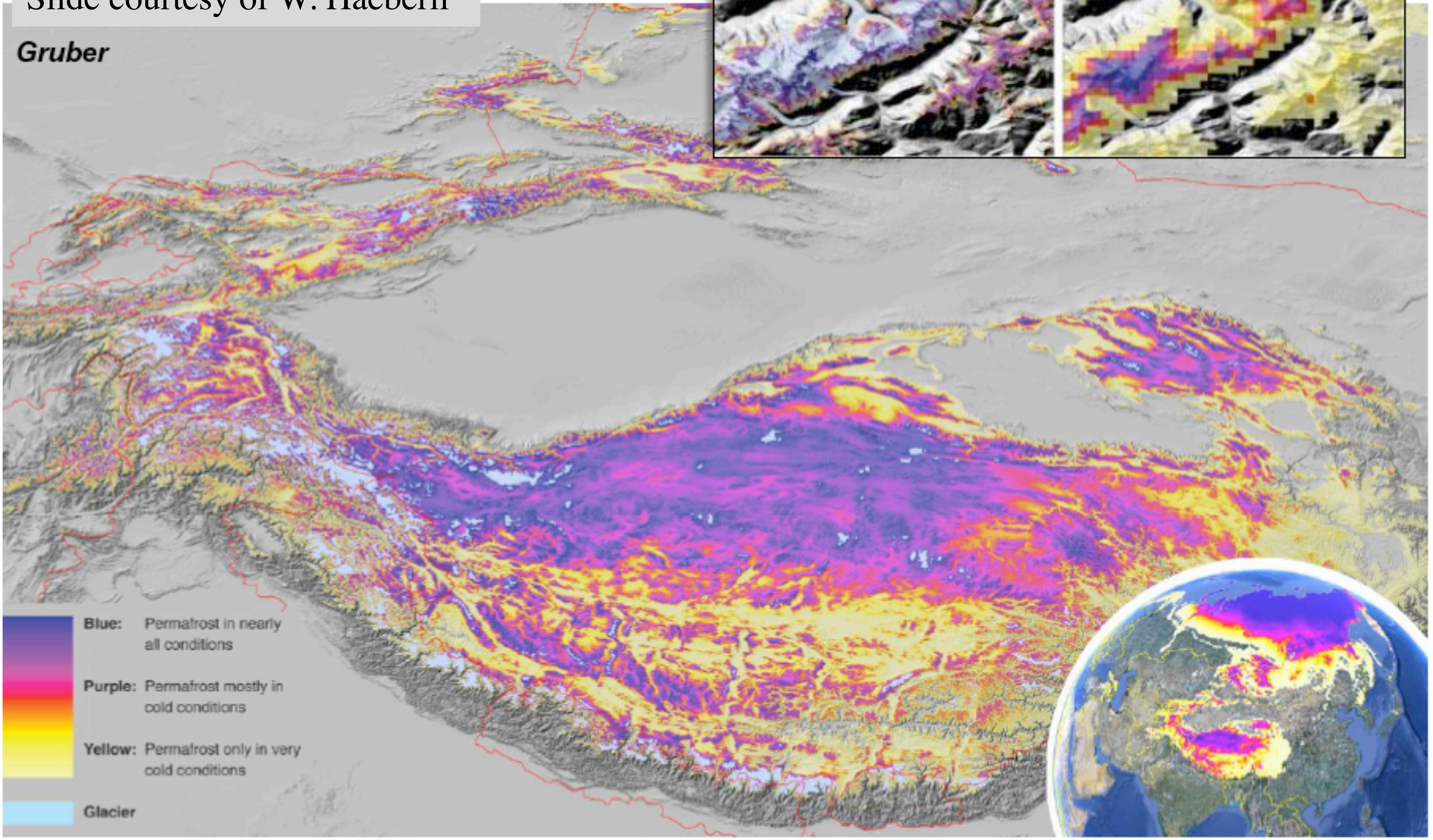
Thermokarst

Characteristic landforms from thawing of ice-rich permafrost or melting of massive ice blocks.

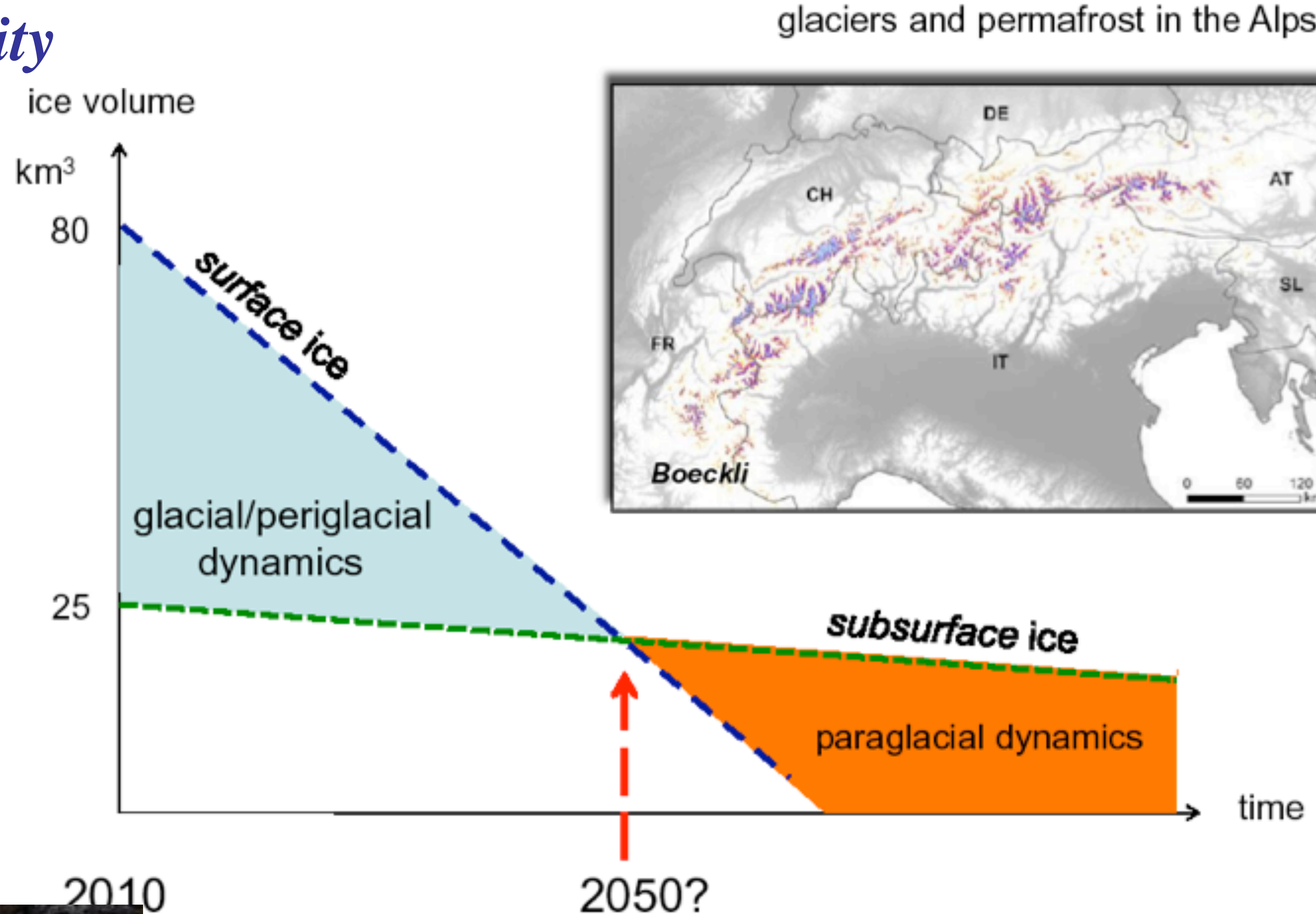
Characterized by irregular topography as irregular pits and depressions develop by thaw settling.

Mountain permafrost and geohazards:

Slide courtesy of W. Haeberli



Changing water availability

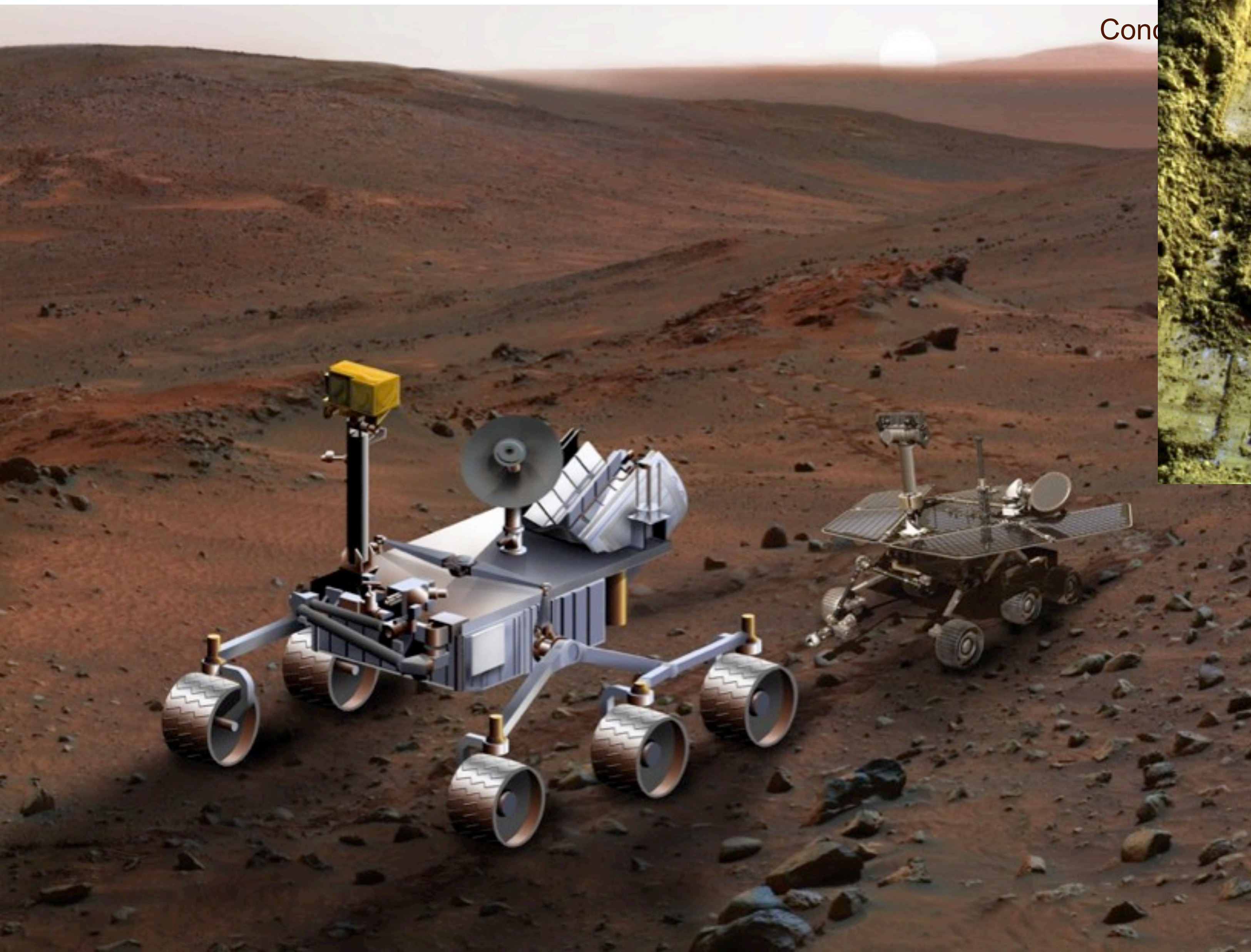


Figures above courtesy of W. Haeberli

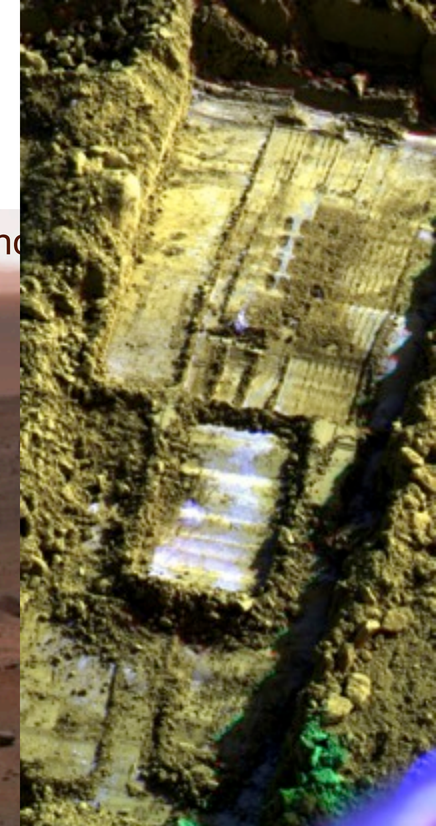
Vulnerable villager & prayer stones, Khumbu region

Exploration of Mars, THE permafrost planet

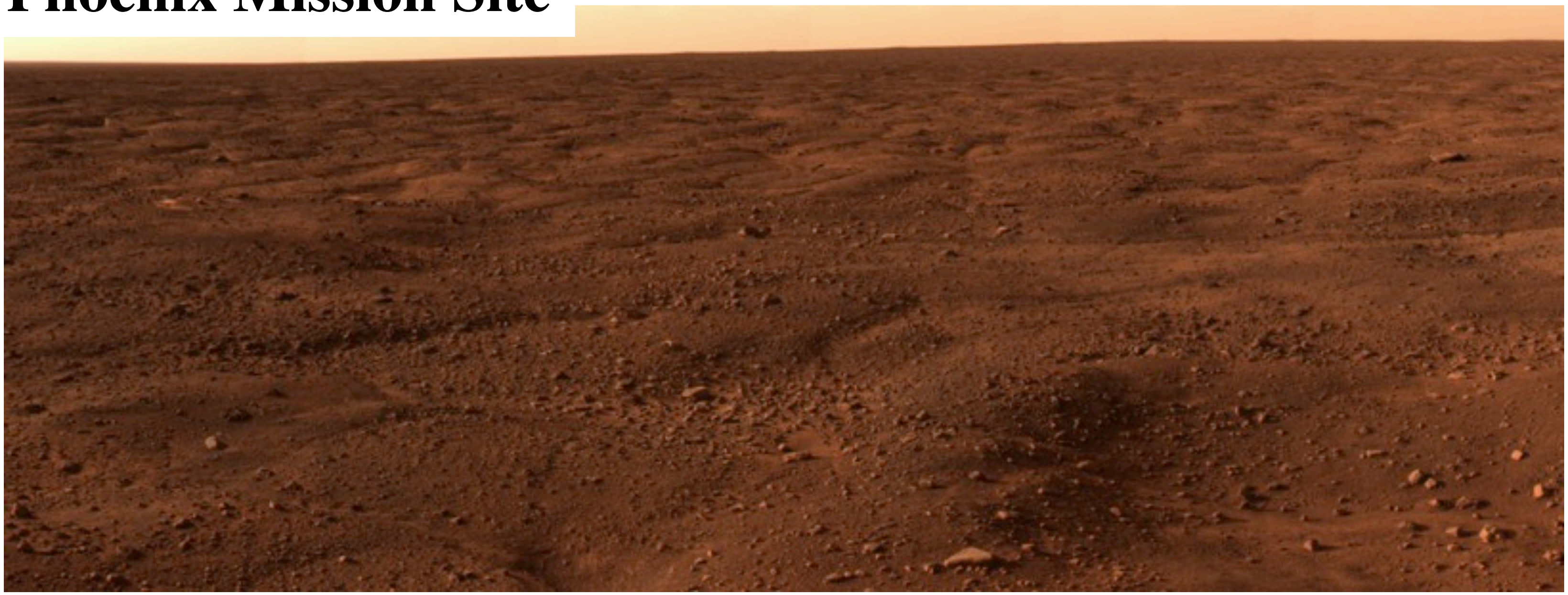
Phoenix Mission to a high latitude site largely to examine near surface ice, 2008; Mars Science Laboratory, 2012

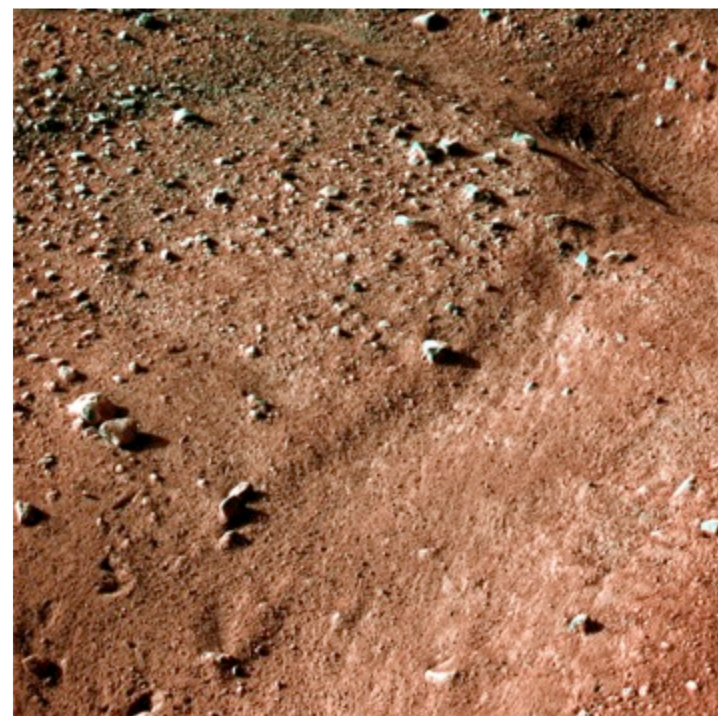


Conc



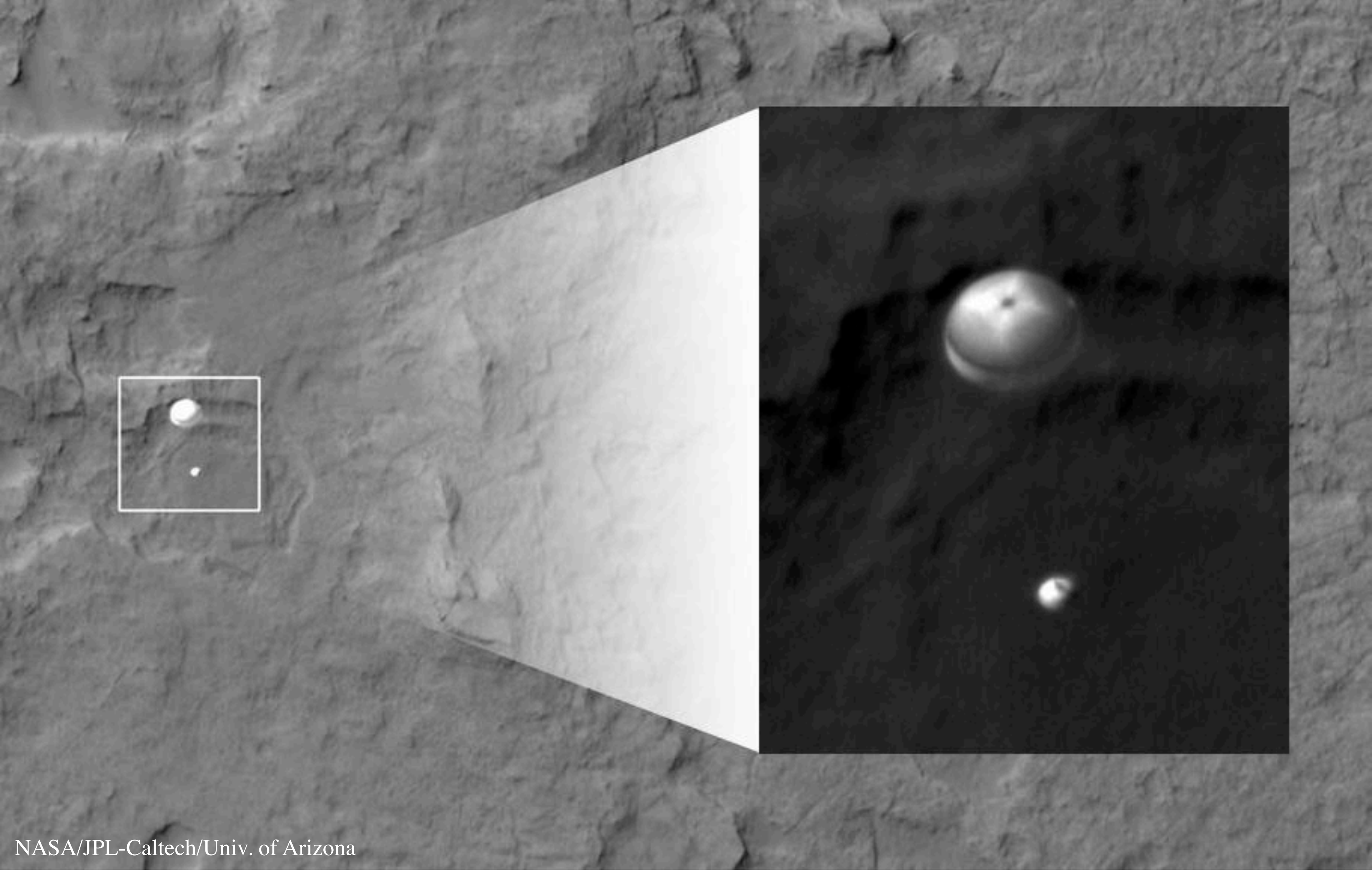
Phoenix Mission Site



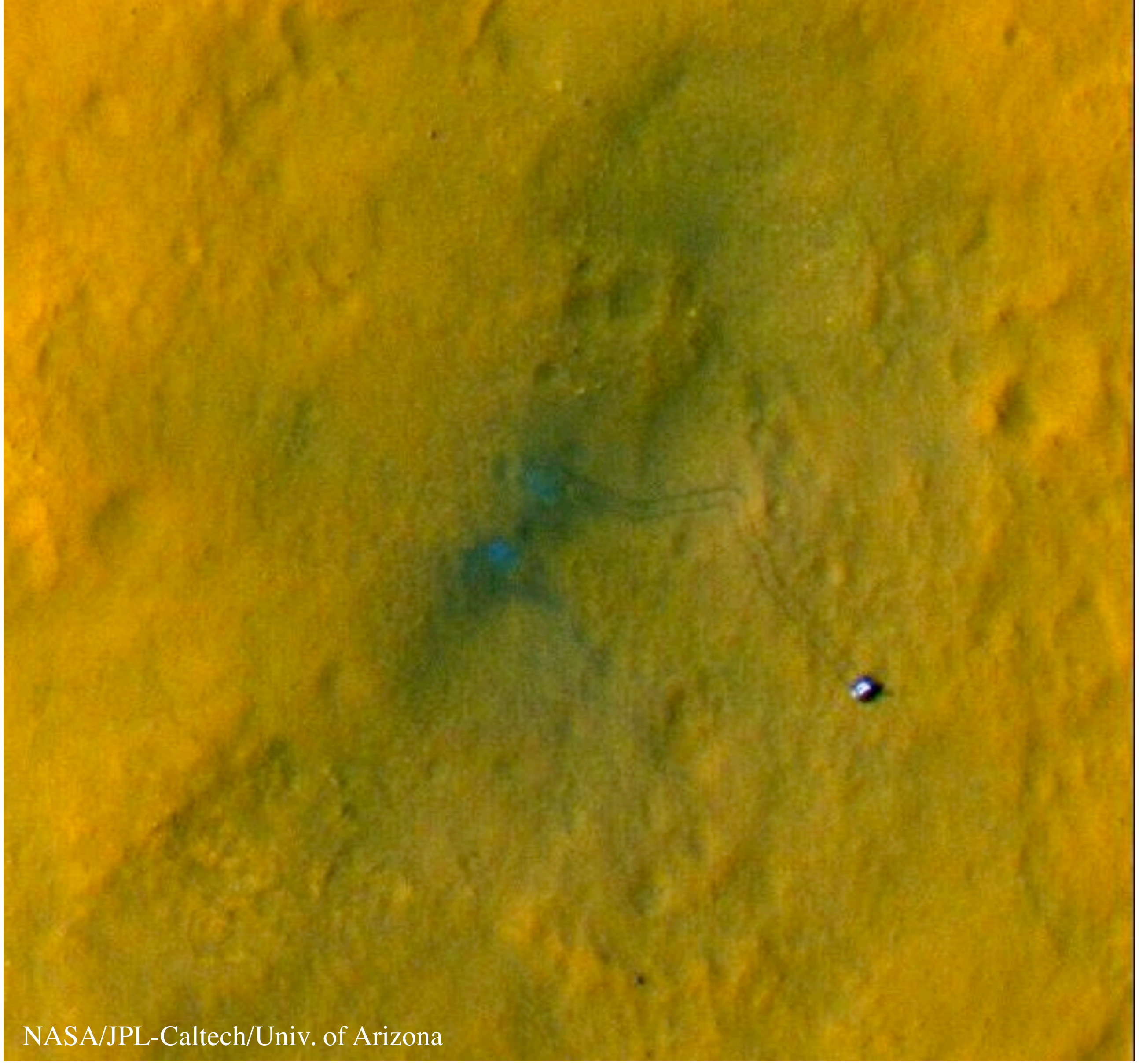


Curiosity’s primary scientific goal is to explore and quantitatively assess a local region on Mars’ surface as a potential habitat for life, past or present

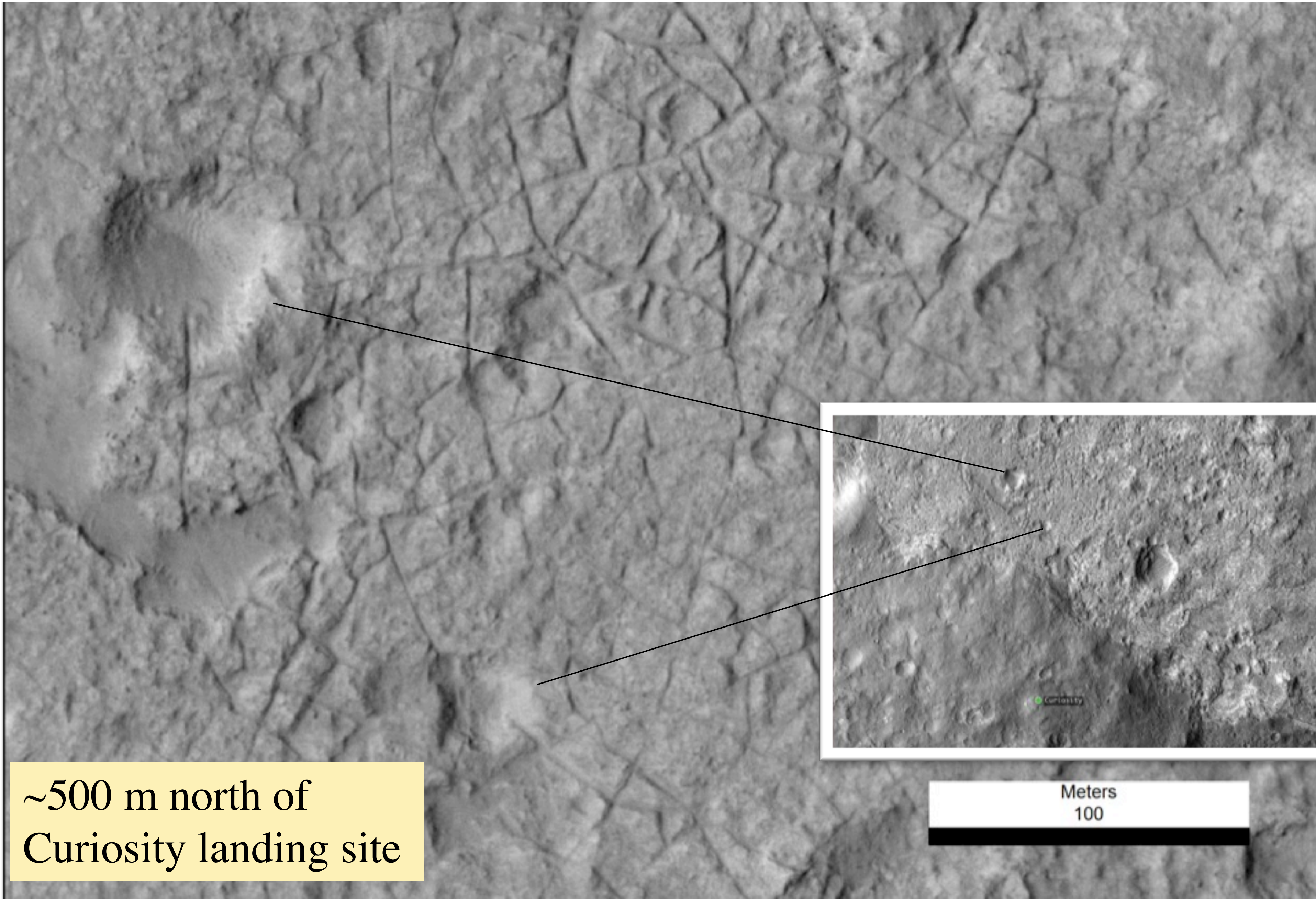
- Biological potential
- Geology and geochemistry
- Role of water
- Surface radiation



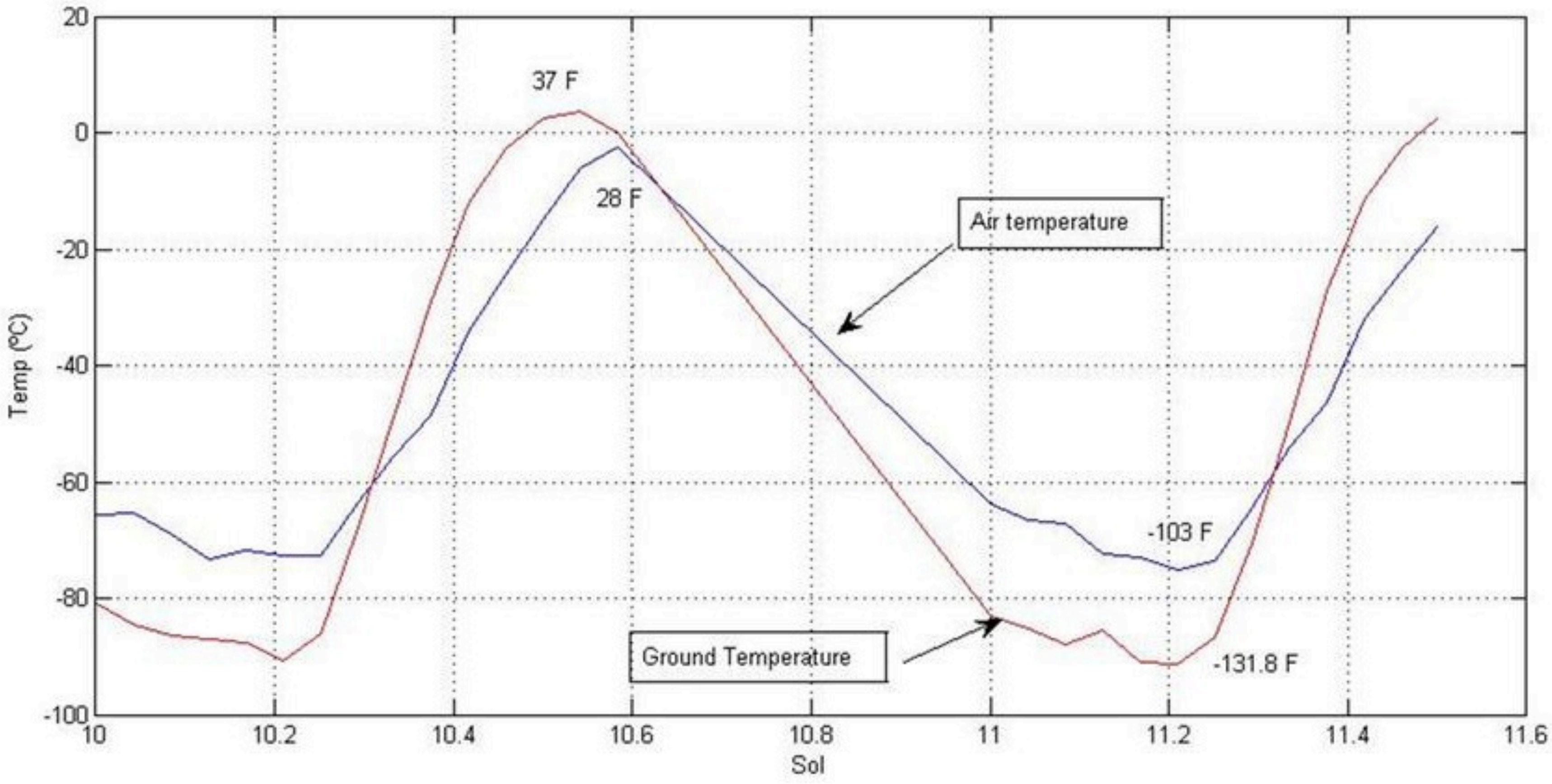
CURIOSITY



HIRISE images a few days after landing


Curiosity
Meters
100
~500 m north of
Curiosity landing site

GROUND AND AIR TEMPERATURE SENSOR



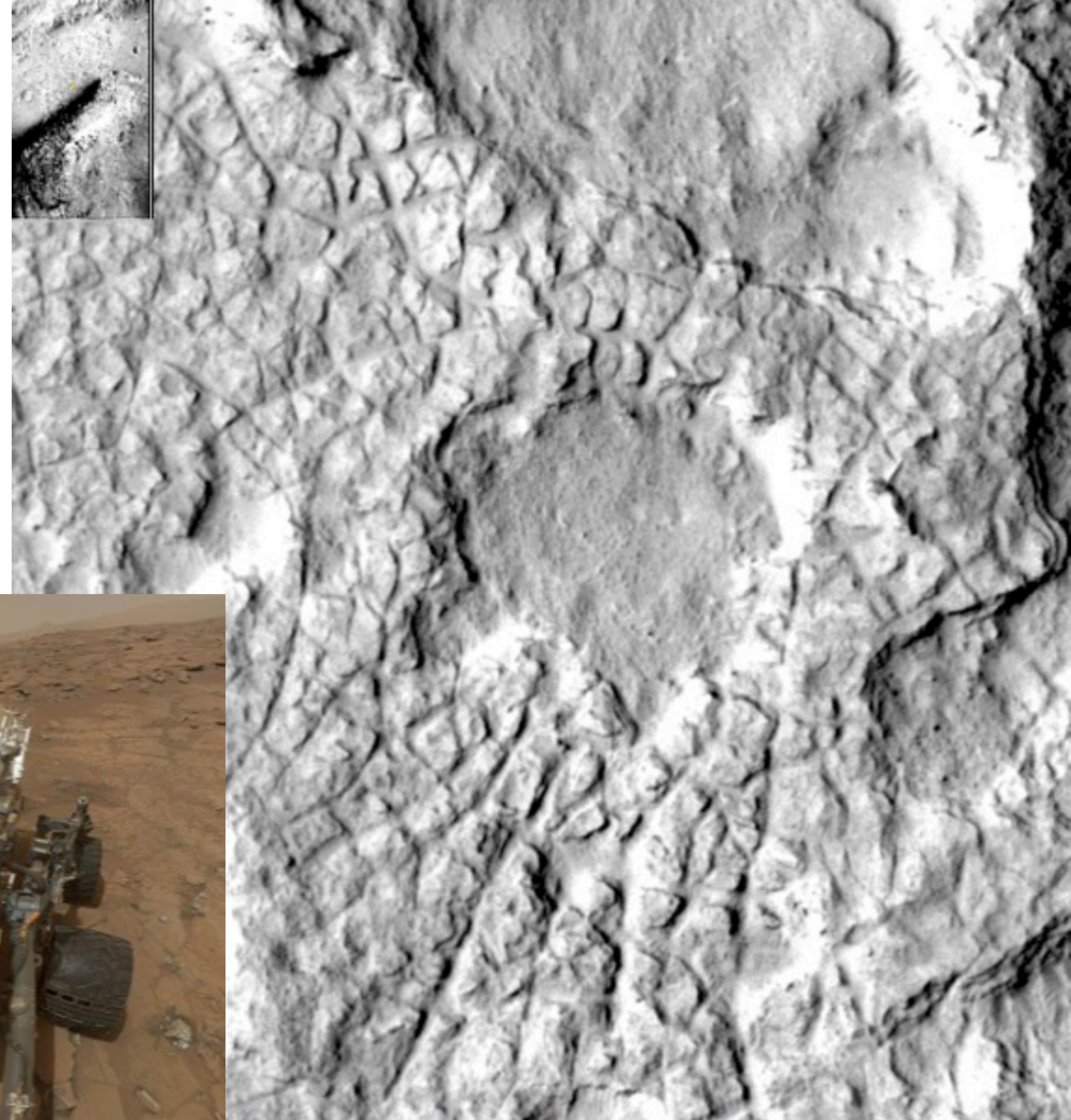
Sol

CURIOSITY

Permafrost prevails even at equator, mean T about -50° C

Fracture patterns ubiquitous on Mars

But is contraction due to cooling or drying?



20 m polygons at Gale, Mars

Summary

Rich issues:

Thermal regime & the warming Arctic: complex system

Soil is well known to expand, heave, and crack as it freezes because of molecular scale properties of H_2O in confined spaces, and thermal stresses

Patterned ground: spectacular expressions of abiotic self-organization in Nature

Other characteristic periglacial landforms

Ice & Frozen ground on Mars: Earth provides instructive analogs

Useful references

Taber, S. 1929. Frost heaving, *Journal of Geology*, **37**, 428-461.

Rosenberg, R. 2005. Why is ice slippery? Physics Today, 50-55.

Wettlaufer, J. S. and J.G. Dash, 2000, Melting below zero, *Scientific American*, 282(2), 50-53.

Stone Circles, Spitsbergen