Динамика вечной мерзлоты и цикл углерода в Арктике

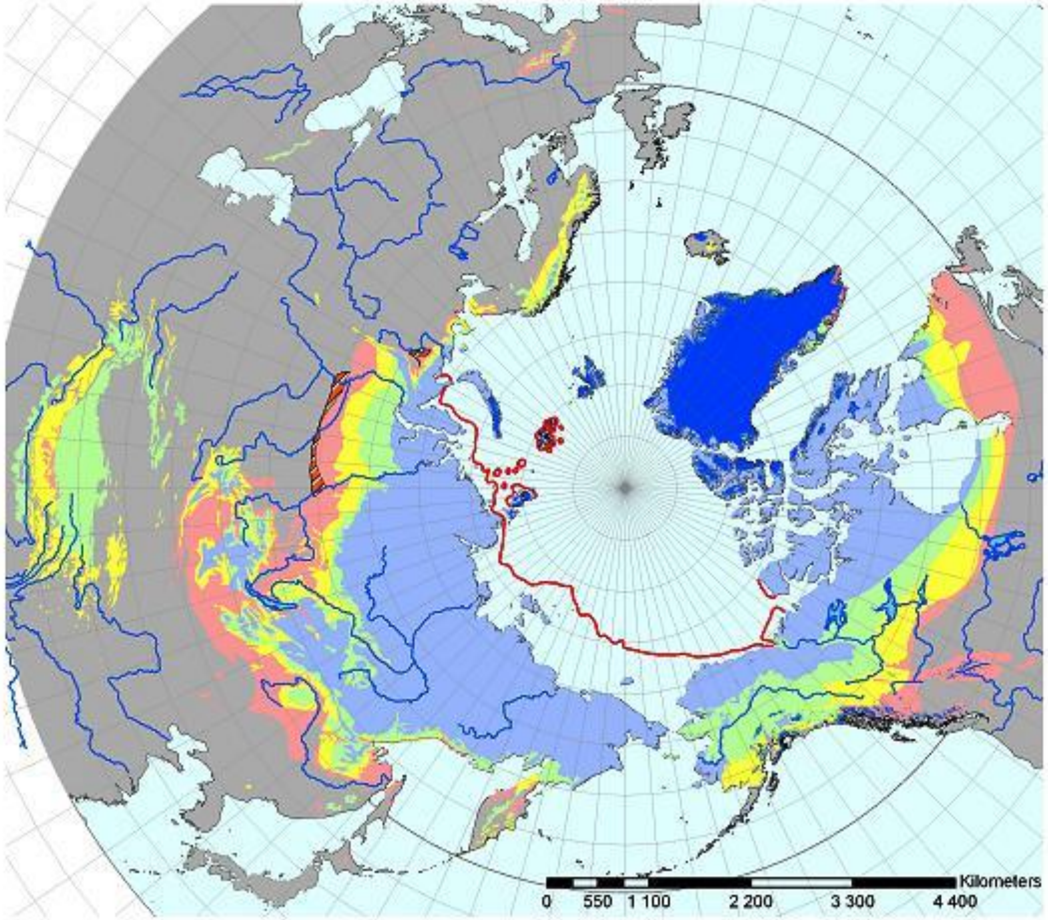
Vladimir Romanovsky

University of Alaska Fairbanks

UNIVERSITY OF ALASKA FAIRBANKS

Circumpolar permafrost extent

Permafrost Lab., GI UAF, 2003



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Geophysical Institute - University of Alaska Fairbanks

Legend

Permafrost extent

- Continious (90-100% of area)
- Discontinious (50-90% of area)
- Sporadic (10-50% of area)
- Isolated (0-10% of area)

Subsea cryosphere

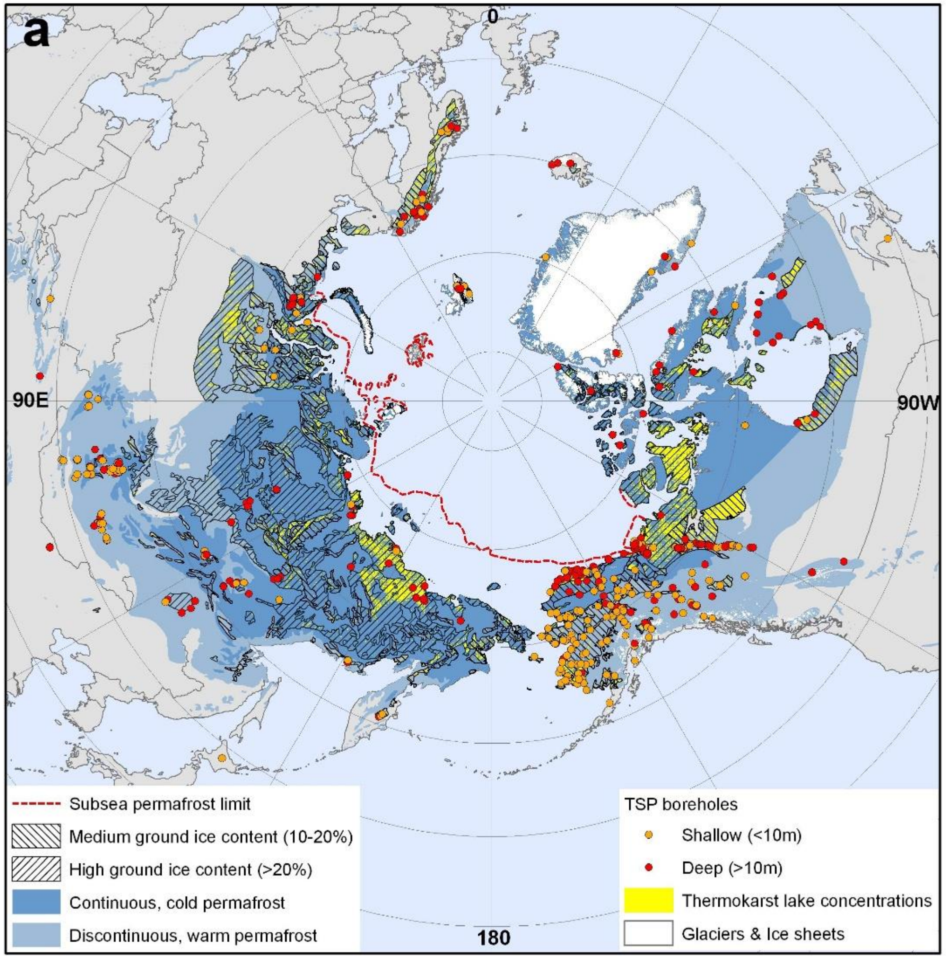
- Subsea permafrost limit

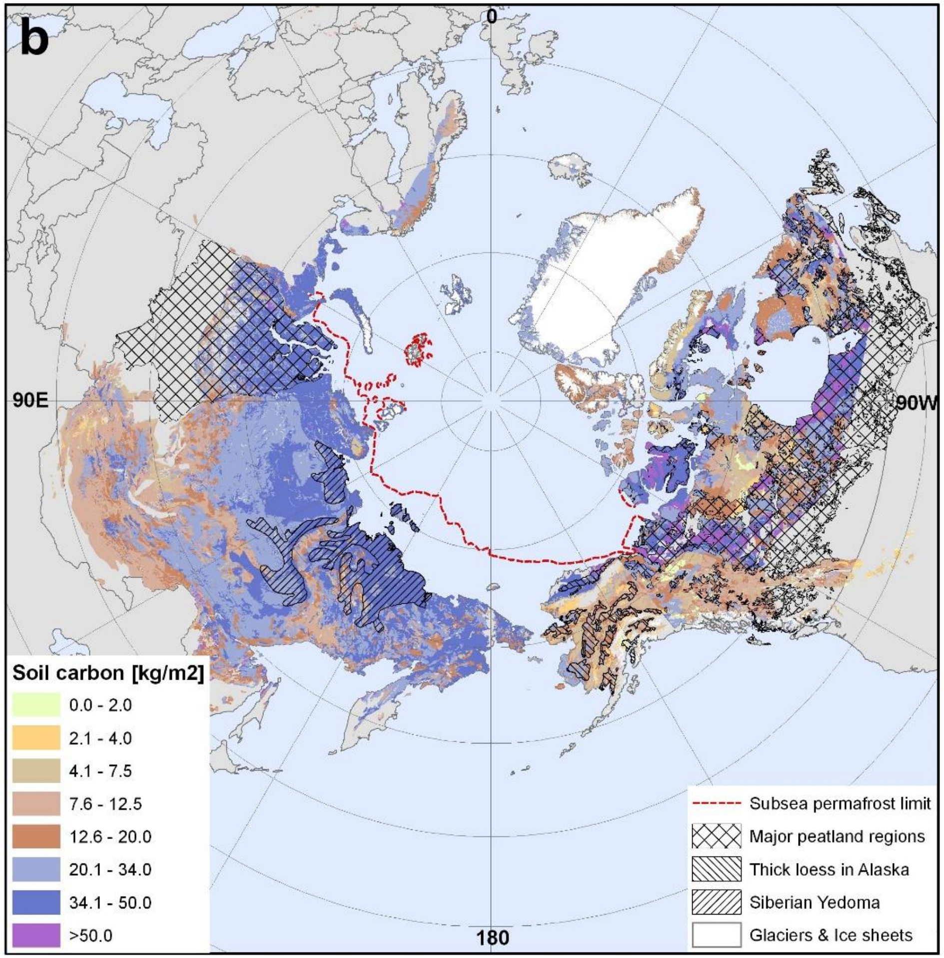
Relict permafrost

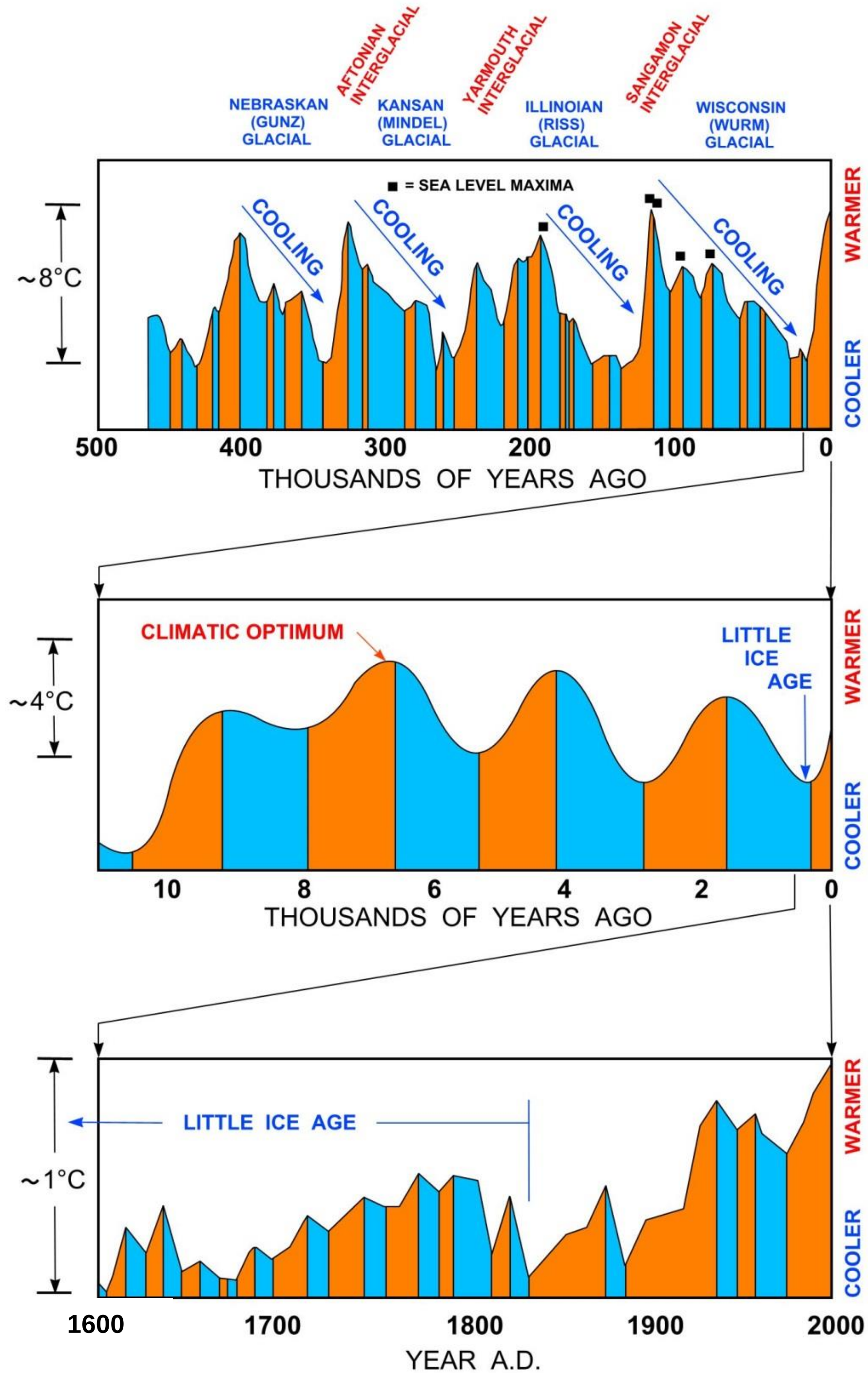
Geograpic objects

- Glaciers
- Lakes
- Ocean and Seas
- Land
- Rivers
- 10 x 10 Degree Graticule

This map was prepared by using an electronic version of the "Circum-Arctic Map of Permafrost and Ground-Ice Condition", J.Brown, O.J. Ferrians, Jr., J.A. Heginbottom, & E.S.Melnikov, 1997, U.S.Geological Survey, ISBN 0-607-88745-1.

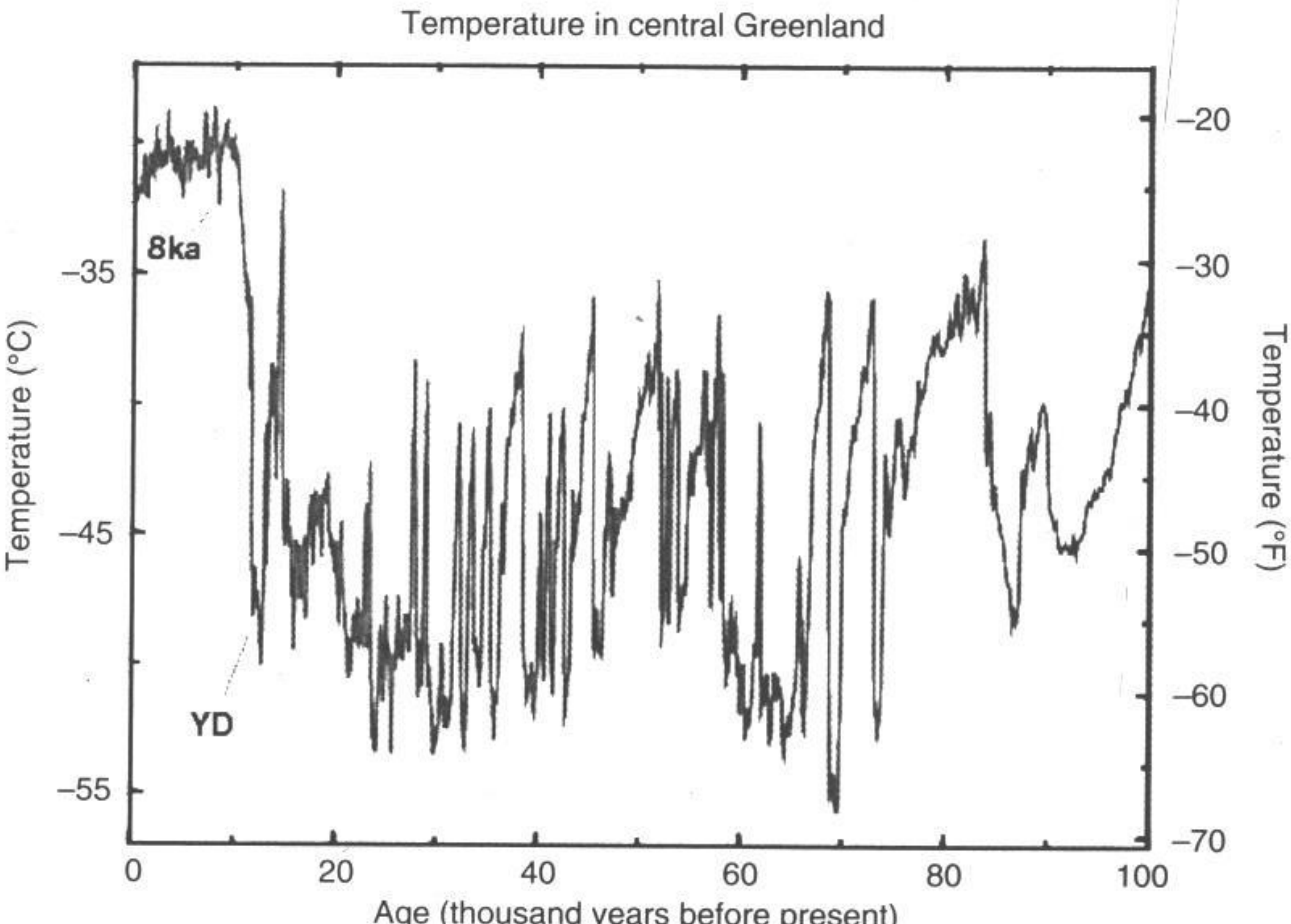

a
0
90E
90W
180
Subsea permafrost limit
Medium ground ice content (10-20%)
High ground ice content (>20%)
Continuous, cold permafrost
Discontinuous, warm permafrost
TSP boreholes
Shallow (<10m)
Deep (>10m)
Thermokarst lake concentrations
Glaciers & Ice sheets


b
0
90E
90W
180
Soil carbon [kg/m2]
0.0 - 2.0
2.1 - 4.0
4.1 - 7.5
7.6 - 12.5
12.6 - 20.0
20.1 - 34.0
34.1 - 50.0
>50.0
Subsea permafrost limit
Major peatland regions
Thick loess in Alaska
Siberian Yedoma
Glaciers & Ice sheets


NEBRASKAN (GUNZ) GLACIAL
AFTONIAN INTERGLACIAL
KANSAN (MINDEL) GLACIAL
YARMOUTH INTERGLACIAL
ILLINOIAN (RISS) GLACIAL
SANGAMON INTERGLACIAL
WISCONSIN (WURM) GLACIAL
■ = SEA LEVEL MAXIMA
COOLING
COOLING
COOLING
COOLING
~8°C
WARMER
COOLER
500
400
300
200
100
0
THOUSANDS OF YEARS AGO
CLIMATIC OPTIMUM
LITTLE ICE AGE
~4°C
WARMER
COOLER
10
8
6
4
2
0
THOUSANDS OF YEARS AGO
LITTLE ICE AGE
~1°C
WARMER
COOLER
1600
1700
1800
1900
2000
YEAR A.D.

Late Pleistocene includes

- Previous interglacial – generally warmer than now
- First phase of the Glacial Period
  cold (5-10°C colder than now) Early Wisconsin: 73-58 ka ago
- Middle Wisconsin – warmer a bit: 58-31 ka ago
- Late Wisconsin – very cold (the coldest): 31-14 ka ago
  global sea level was lower by 120-130 m than now
- A sharp turn to a warmer climate: 15-14 ka ago



Temperature in central Greenland
8ka
YD
Temperature (°C)
-35
-45
-55
Temperature (°F)
-20
-30
-40
-50
-60
-70
0
20
40
60
80
100
Age (thousand years before present)

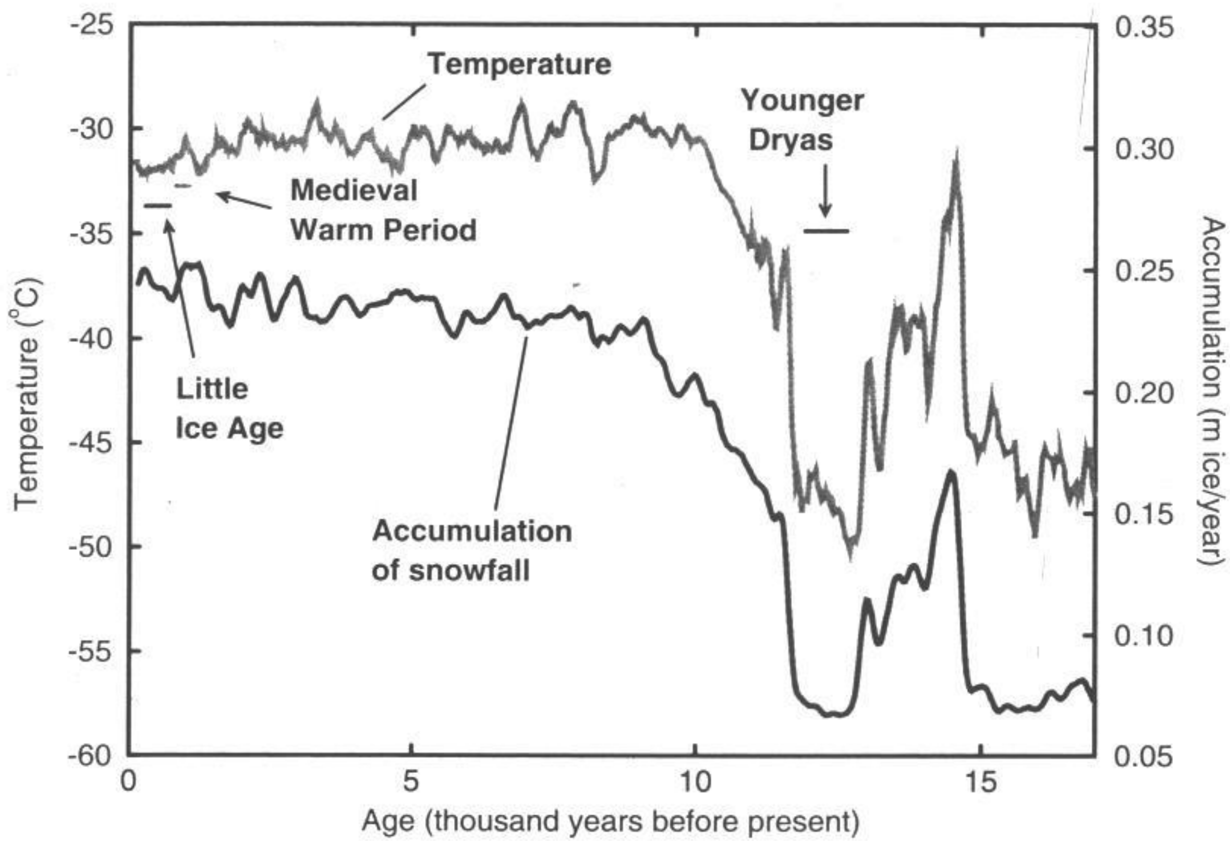
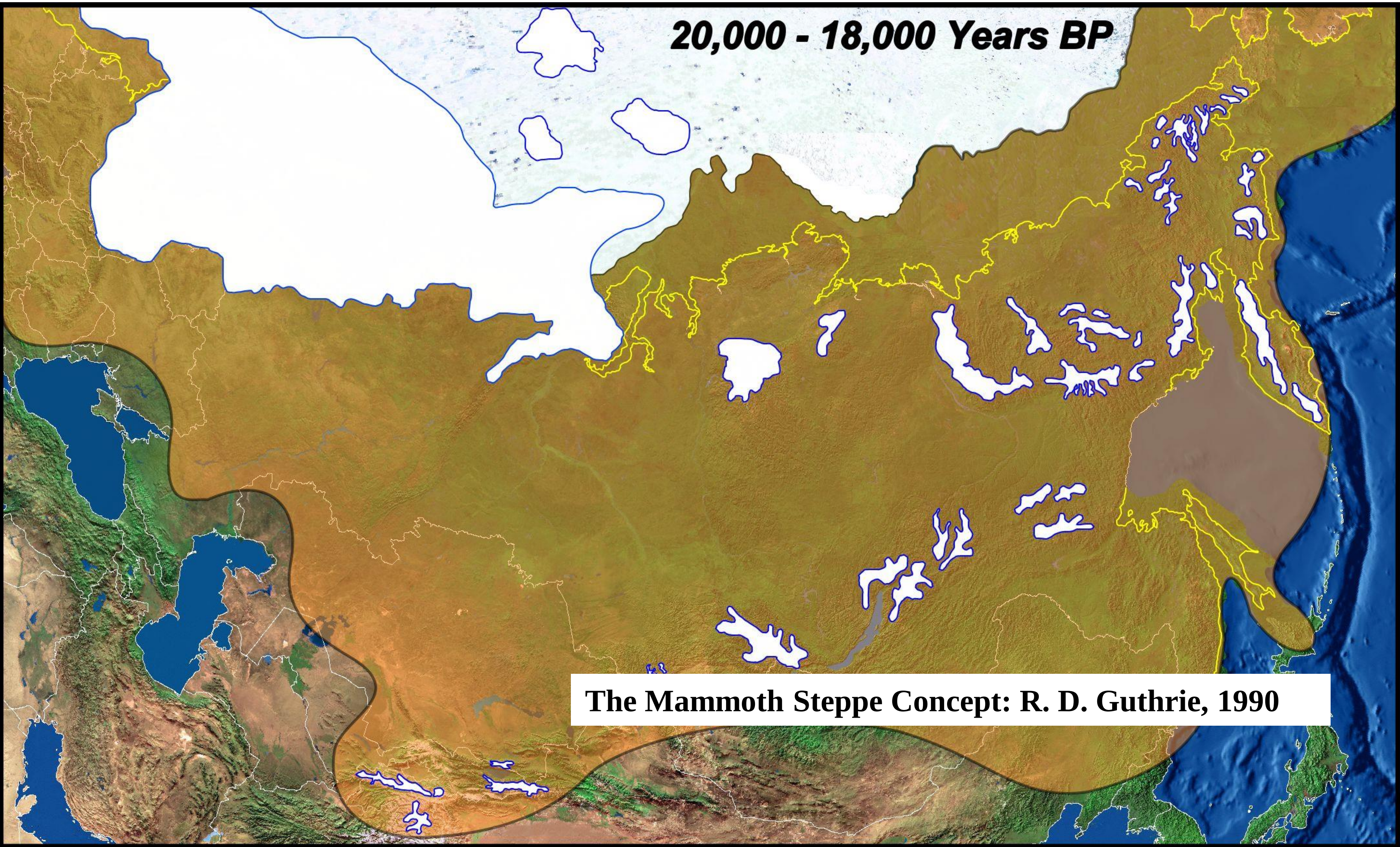


FIGURE 1.2 Climate changes in central Greenland over the last 17,000 years. Reconstructions of temperature and snow accumulation rate (Cuffey and Clow, 1997; Alley, 2000) show a large and rapid shift out of the ice age about 15,000 years ago, an irregular cooling into the Younger Dryas event, and the abrupt shift toward modern values. The 100-year averages shown somewhat obscure the rapidity of the shifts. Most of the warming from the Younger Dryas required about 10 years, with 3 years for the accumulation-rate increase (Figure 2.2). A short-lived cooling of about 6°C occurred about 8,200 years ago (labeled 8ka event), and is shown with higher time resolution in Figure 2.3. Climate changes synchronous with those in Greenland affected much of the world, as shown in Figures 2.1 and 2.3.


20,000 - 18,000 Years BP
The Mammoth Steppe Concept: R. D. Guthrie, 1990

The Mammoth Steppe Concept: R. D. Guthrie, 1990

Dan Mann holds the skull of a steppe bison that died on Alaska's North Slope more than 40,000 years ago.

Photo by Pam Groves

Bison Bob a big discovery on the North Slope

By Ned Rozell

Ice Wedges

Photo by M. Grigoriev

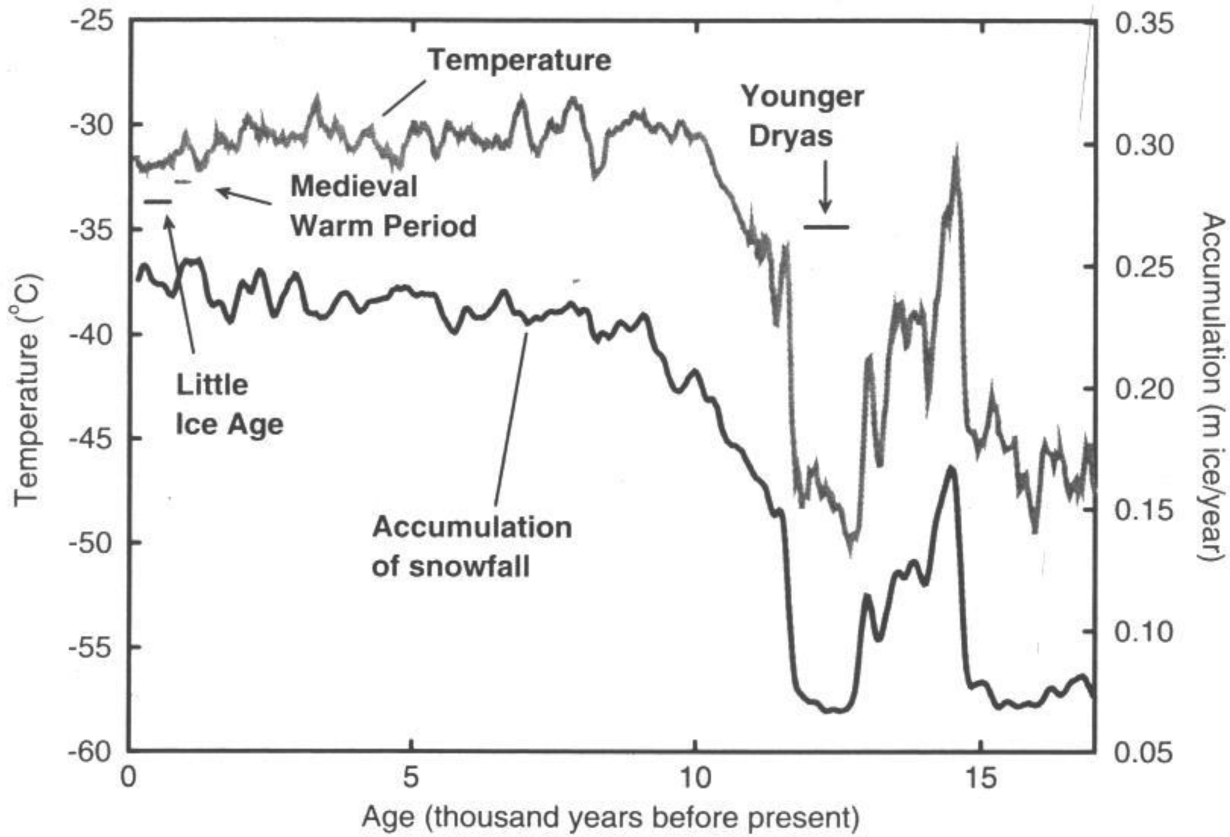


FIGURE 1.2 Climate changes in central Greenland over the last 17,000 years. Reconstructions of temperature and snow accumulation rate (Cuffey and Clow, 1997; Alley, 2000) show a large and rapid shift out of the ice age about 15,000 years ago, an irregular cooling into the Younger Dryas event, and the abrupt shift toward modern values. The 100-year averages shown somewhat obscure the rapidity of the shifts. Most of the warming from the Younger Dryas required about 10 years, with 3 years for the accumulation-rate increase (Figure 2.2). A short-lived cooling of about 6°C occurred about 8,200 years ago (labeled 8ka event), and is shown with higher time resolution in Figure 2.3. Climate changes synchronous with those in Greenland affected much of the world, as shown in Figures 2.1 and 2.3.

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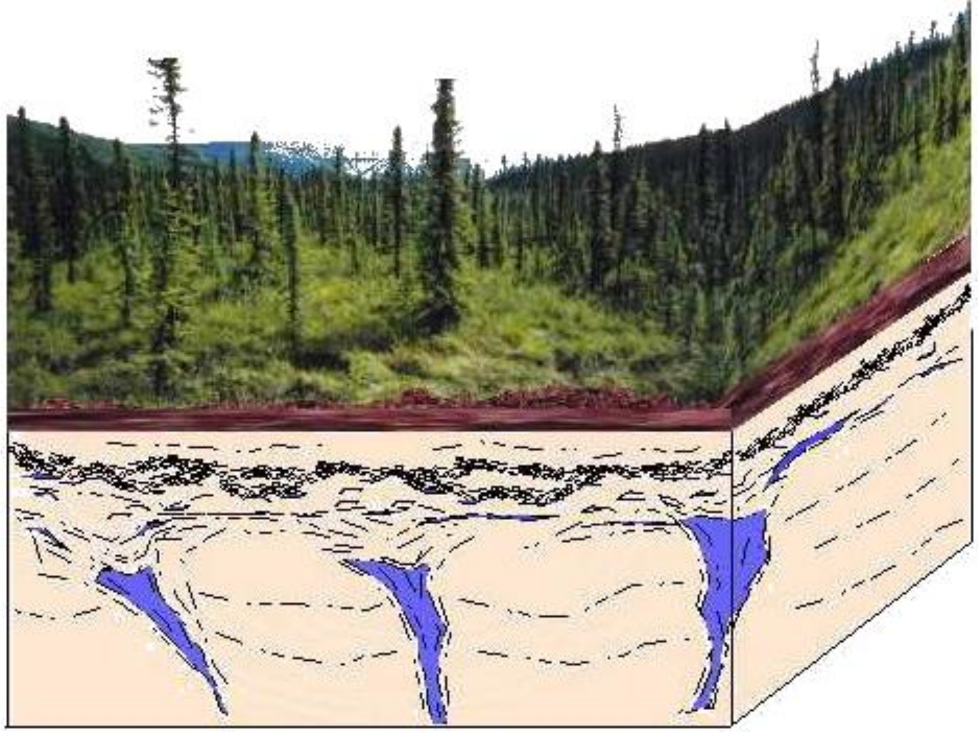
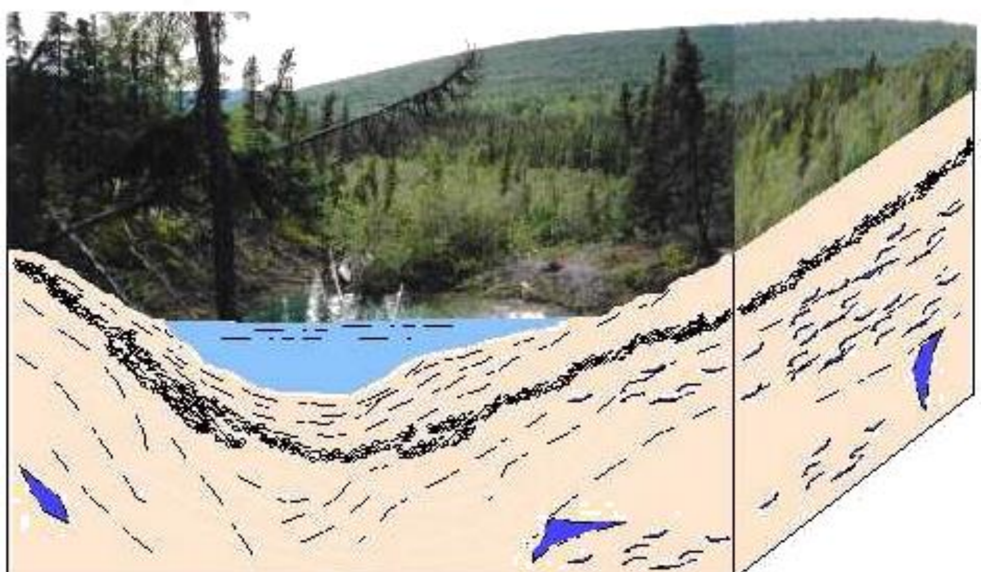
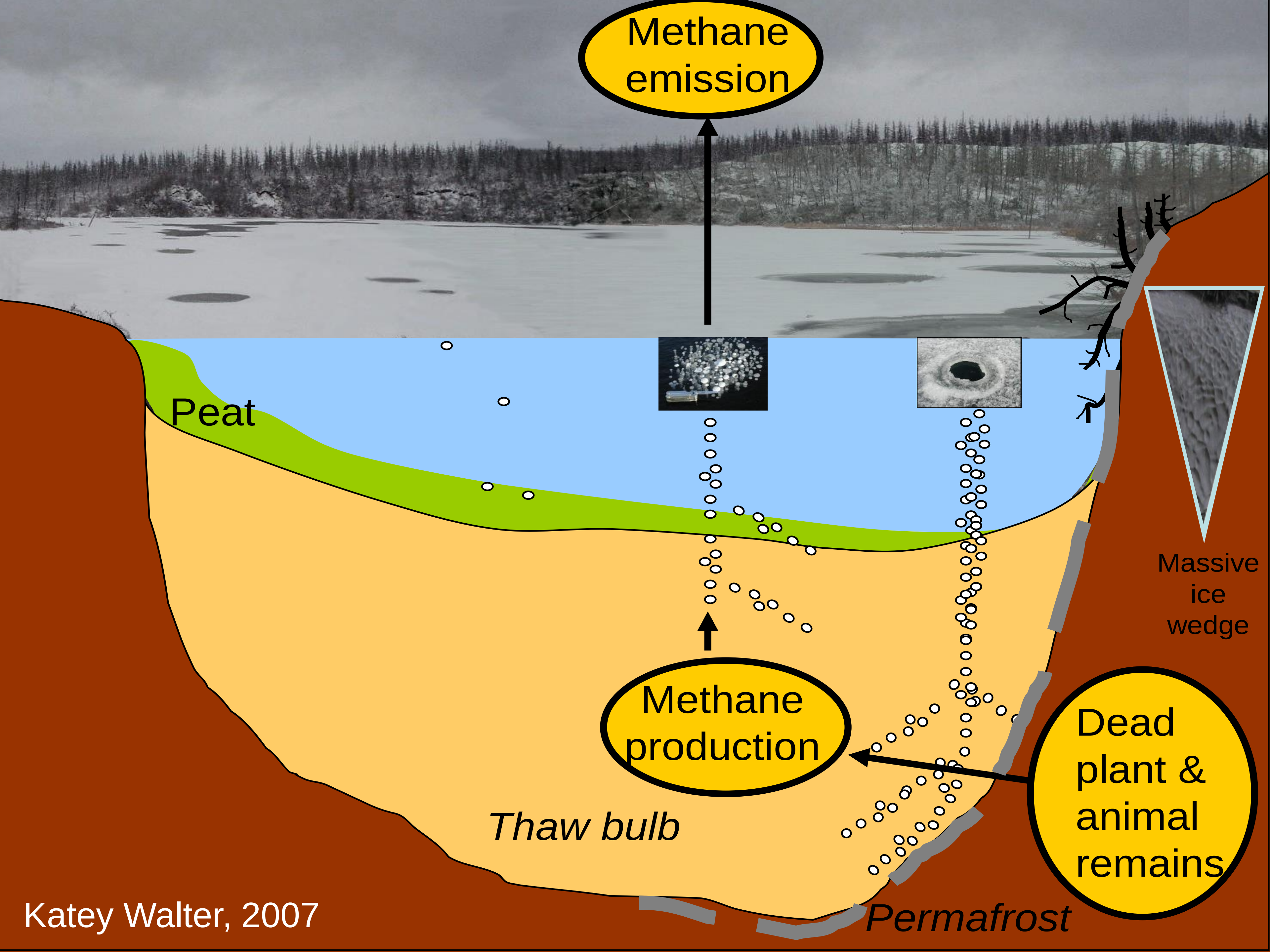
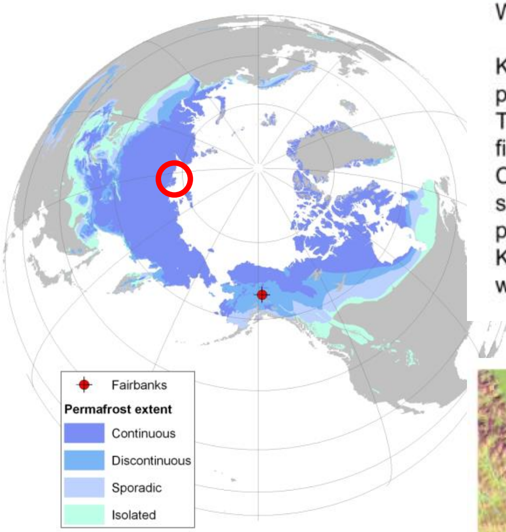
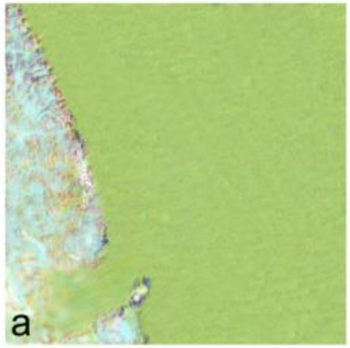




Abrupt Permafrost Thaw

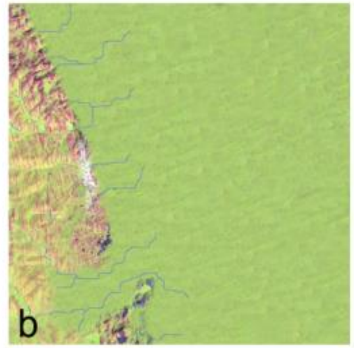

Methane emission
Peat
Massive ice wedge
Methane production
Dead plant & animal remains
Thaw bulb
Permafrost
Katey Walter, 2007





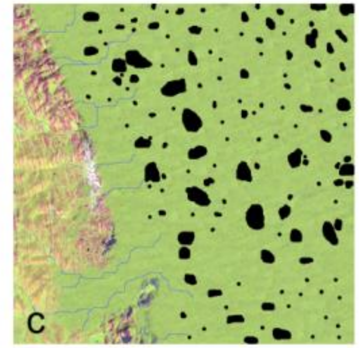
Weichselian 100 - ca. 16 ky BP

Kharaulakh Ridge with extensive perennial snow fields and névés. Thick, ice-rich medium to fine-grained deposits (Ice Complex) accumulate in the subsiding Bykovsky foreland plain. Large valleys like the Khorogor Valley are partly filled with Ice Complex.



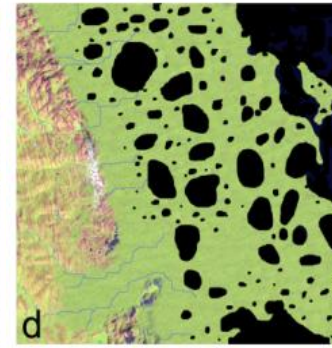
Late Glacial-Holocene transition

Perennial snowfields are strongly reduced in extent. Deposits in the valleys are eroded by increased melt water. Ice Complex accumulation in the foreland plain is decreasing.



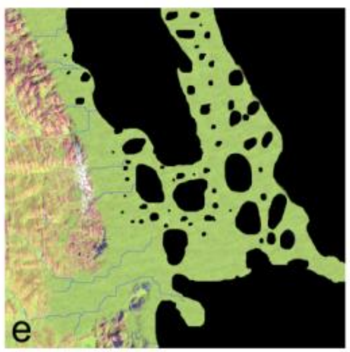
Early Holocene

Start of intense thermokarst development in the plain. Large scale accumulation in the plain changes to a complex pattern of erosion, re-deposition, and accumulation of alas deposits (peats, lake sediments). Ice Complex deposits in the valleys are eroded.



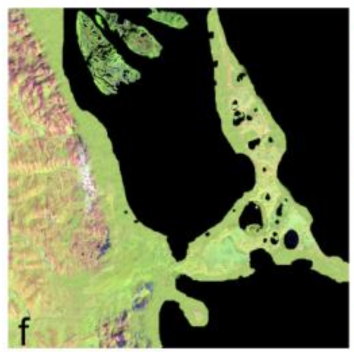
Early-Middle Holocene

Ongoing thermokarst development. The marine transgression results in coastal abrasion, the rapid ingression of thermoarst basins, and the formation of thermokarst lagoons.



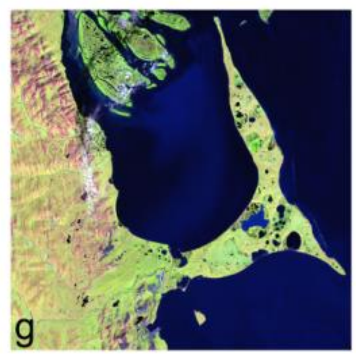
Middle Holocene

Formation of the Neelov and Tiksi Bays due to further tectonic subsidence, thermokarst development and marine ingression. Some depressions drain or silt-up. Talik refreezing and pingo formation begins.



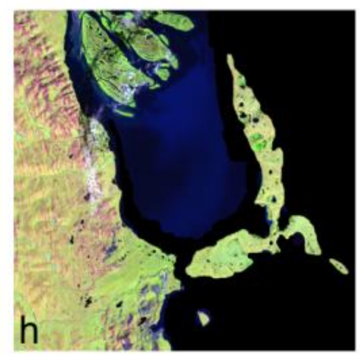
Late Holocene

Decrease of thermokarst development, refreezing of taliks, and pingo growth. Progradation of the Lena Delta into the Neelov Bay.



Recent Holocene

Modern shape and relief. Subset of a Landsat-7 ETM+ image from the 5. August 2000. Further progradation of the SE Lena Delta into the Neelov Bay.



Near future 2050-2500

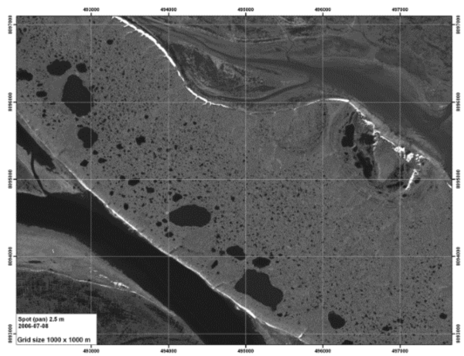
Separation of the Bykovsky Peninsula into islands due to ongoing coastal thermoabrasion, thermokarst subsidence, predicted sea level rise, and marine ingression.

Grosse et al., 2007 (Geomorphology)

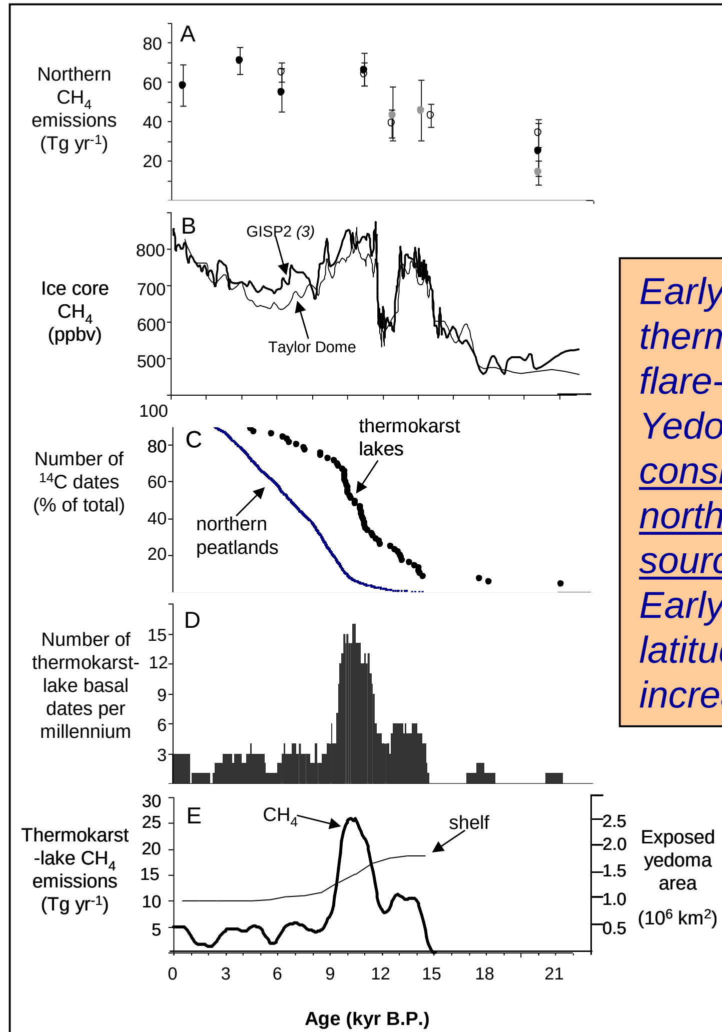
Thermokarst and C-Cycle

Thermokarst Lakes as a Source of Atmospheric CH_4 During the Last Deglaciation

Olenek Channel, Lena Delta



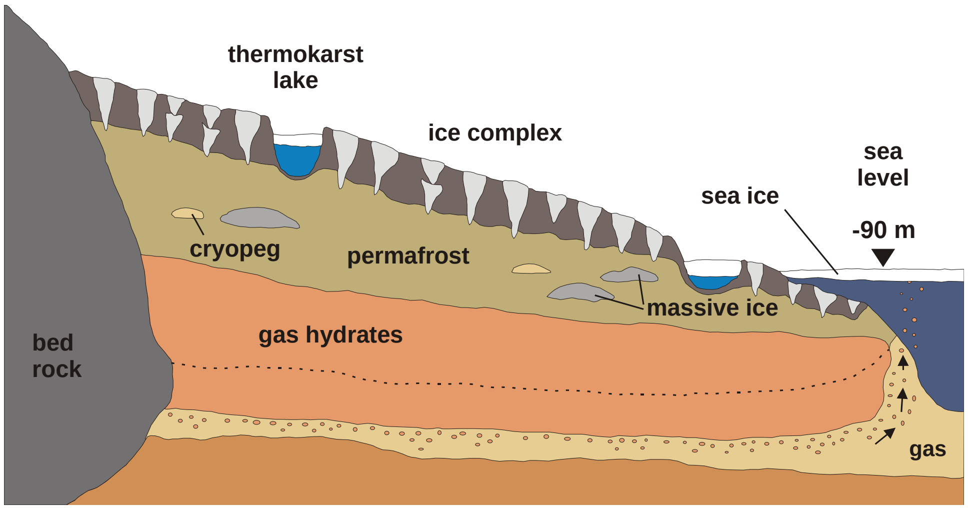
Kolyma Lowland



Early Holocene thermokarst lake flare-up in ice-rich Yedoma was a <u>considerable northern methane source</u> (33-87% of Early Holocene high latitude methane increase).

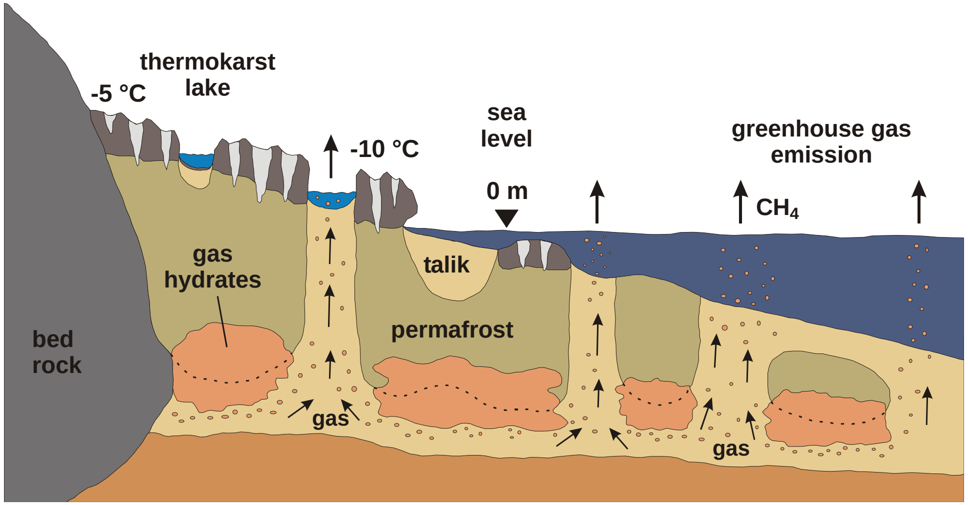
Walter et al, 2007 (Science)

12500 years before present

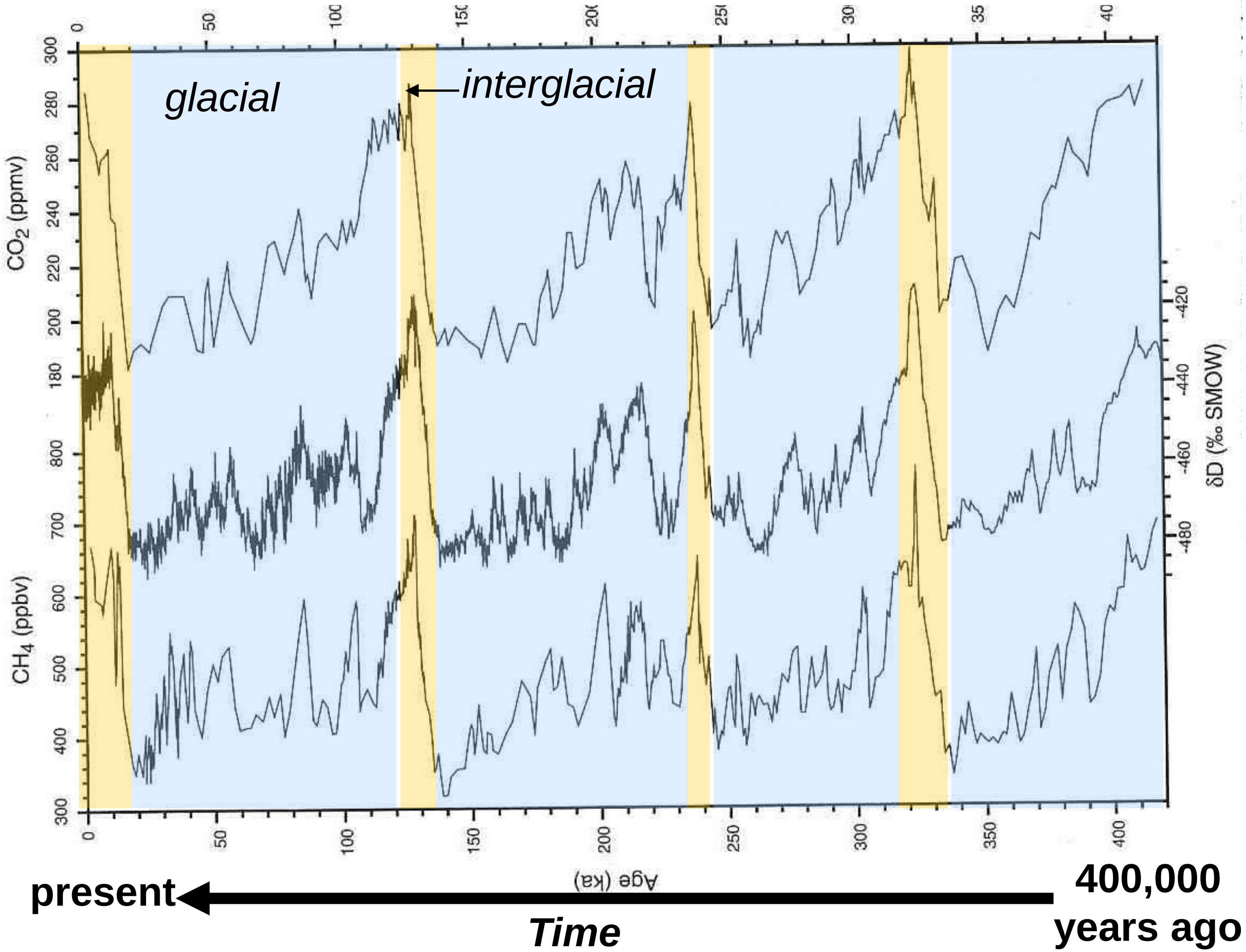


Schematic models of Coastal and Submarine Permafrost distribution under different climatic conditions (after N. Romanovskii)

PRESENT



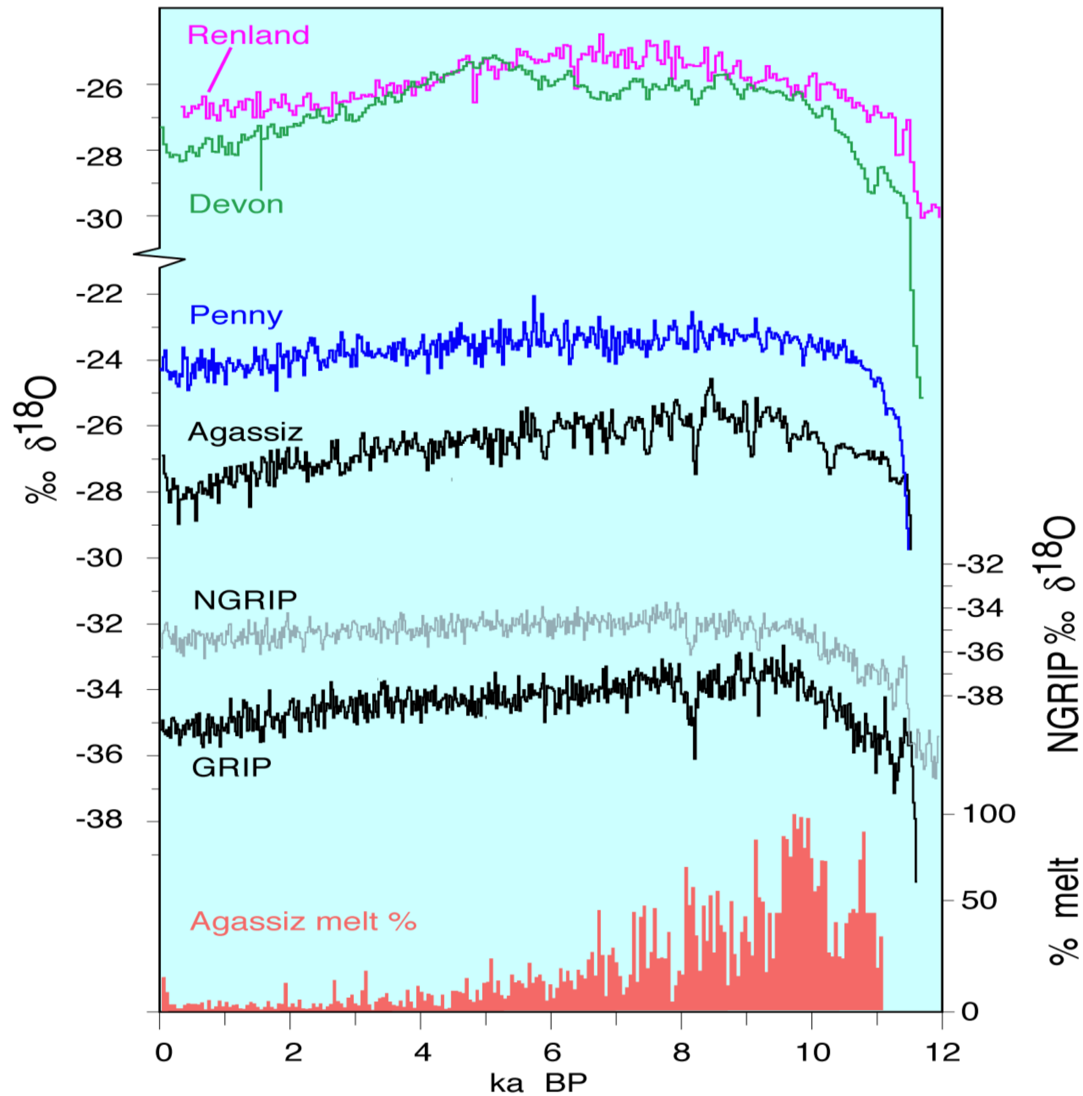
CO_2 and CH_4 in ice cores from Greenland and Antarctica



Late-Holocene Permafrost History

1. Air temperatures were cooling down
2. New “Holocene” permafrost was formed and southern boundary of permafrost moved far south
3. New ice wedges started to grow in cold enough places
4. Vegetation zones moved back south

Holocene δ18O Records from Greenland and Canadian Arctic Ice Caps



Paleoclimate, Global Change and the Future

Alverson, Bradley and Pederson eds., 2002

Chapter 6: R. S. Bradley et al., fig. 6.2, p. 109

GLOBAL IGBP CHANGE

PAGES PAST GLOBAL CHANGES

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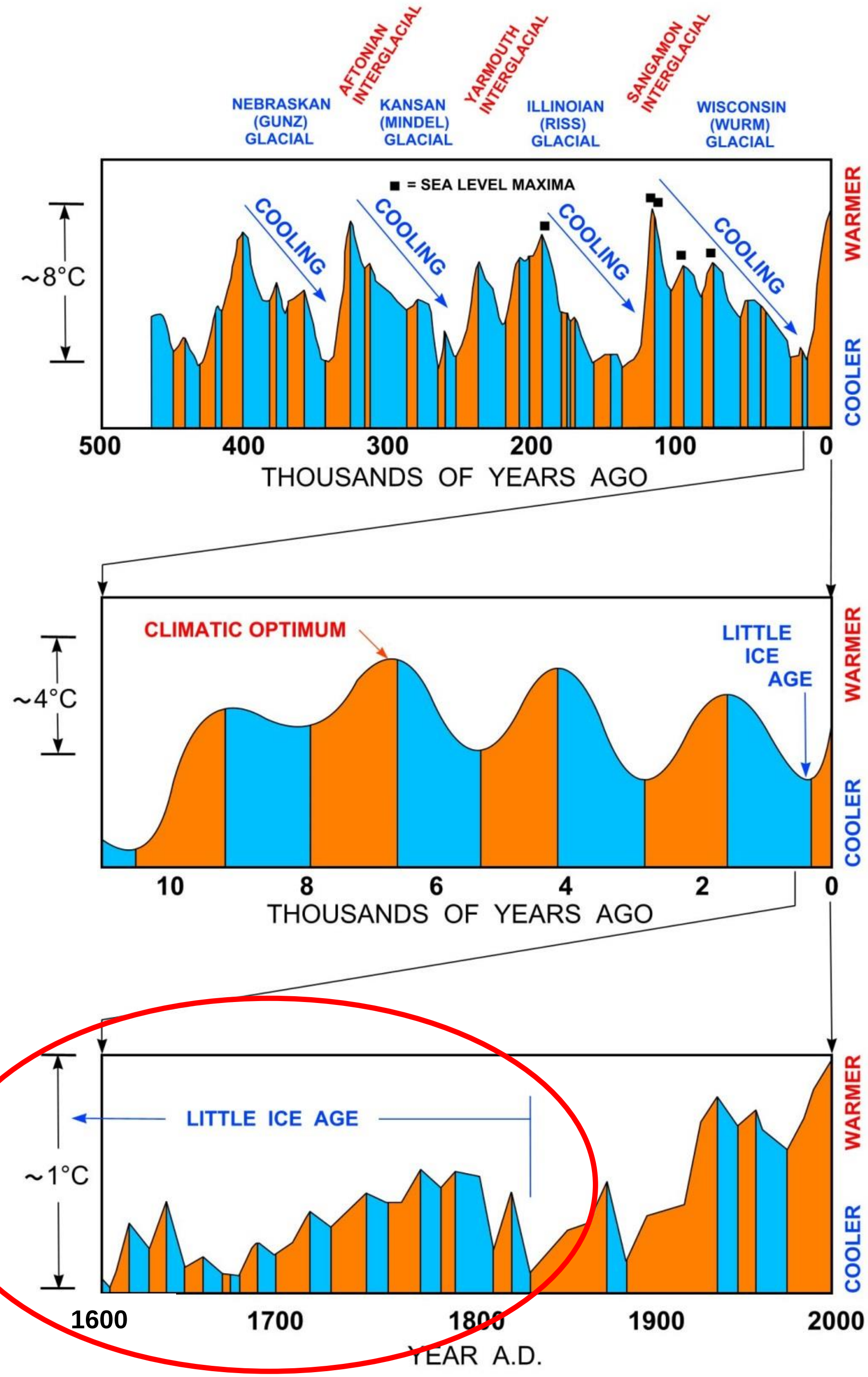

NEBRASKAN (GUNZ) GLACIAL
AFTONIAN INTERGLACIAL
KANSAN (MINDEL) GLACIAL
YARMOUTH INTERGLACIAL
ILLINOIAN (RISS) GLACIAL
SANGAMON INTERGLACIAL
WISCONSIN (WURM) GLACIAL
■ = SEA LEVEL MAXIMA
COOLING
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~8°C
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500
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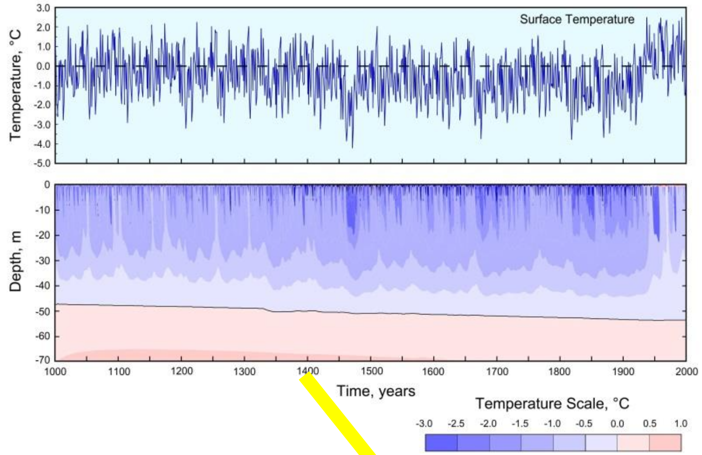
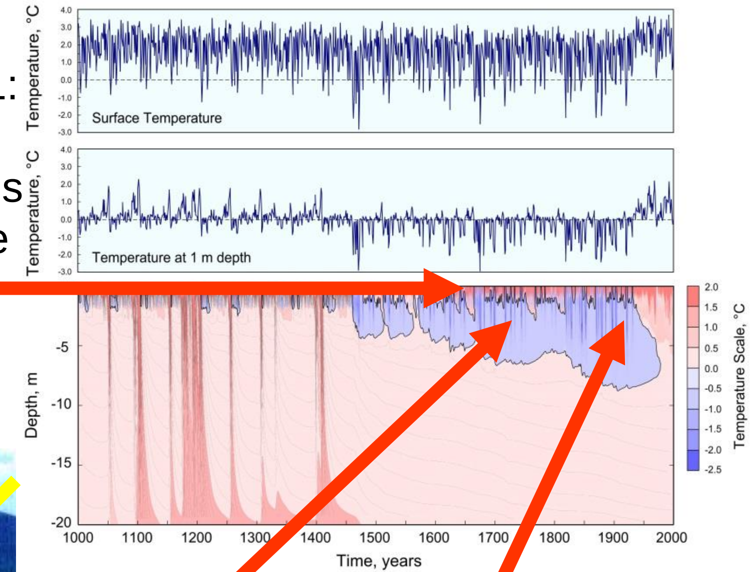
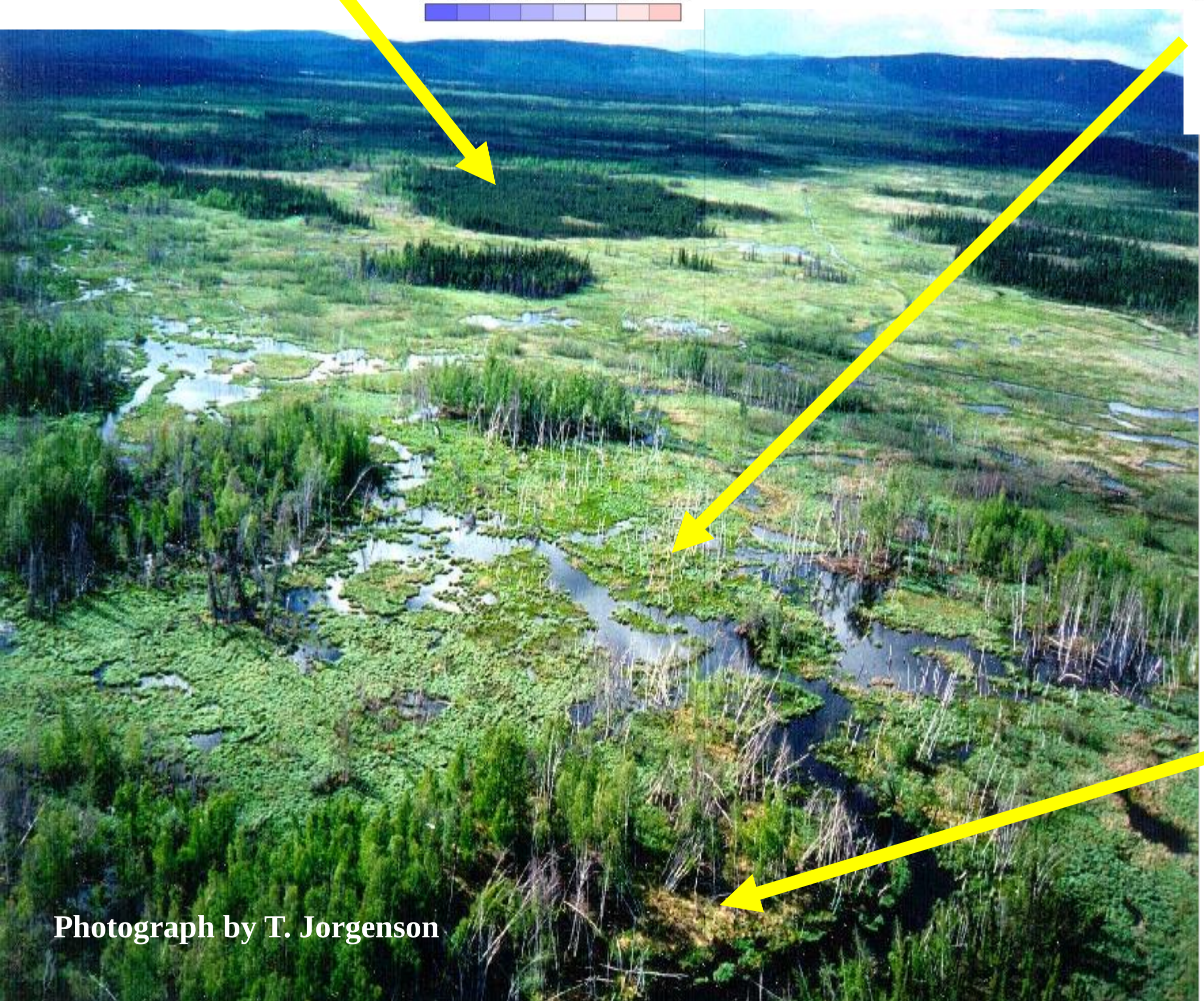
1600
1700
1800
1900
2000
YEAR A.D.

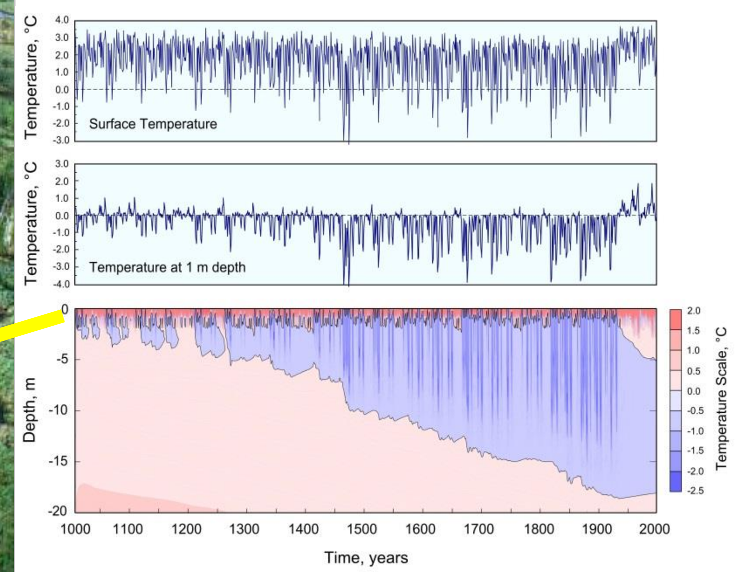


T. Jorgenson et al., 2001: “Permafrost aggradation and the change from fens to forests occurred in the late 1600s.”





“Permafrost degradation began in the mid-1700s and is associated with periods with relatively warm climate during the mid-late 1700s and 1900s”



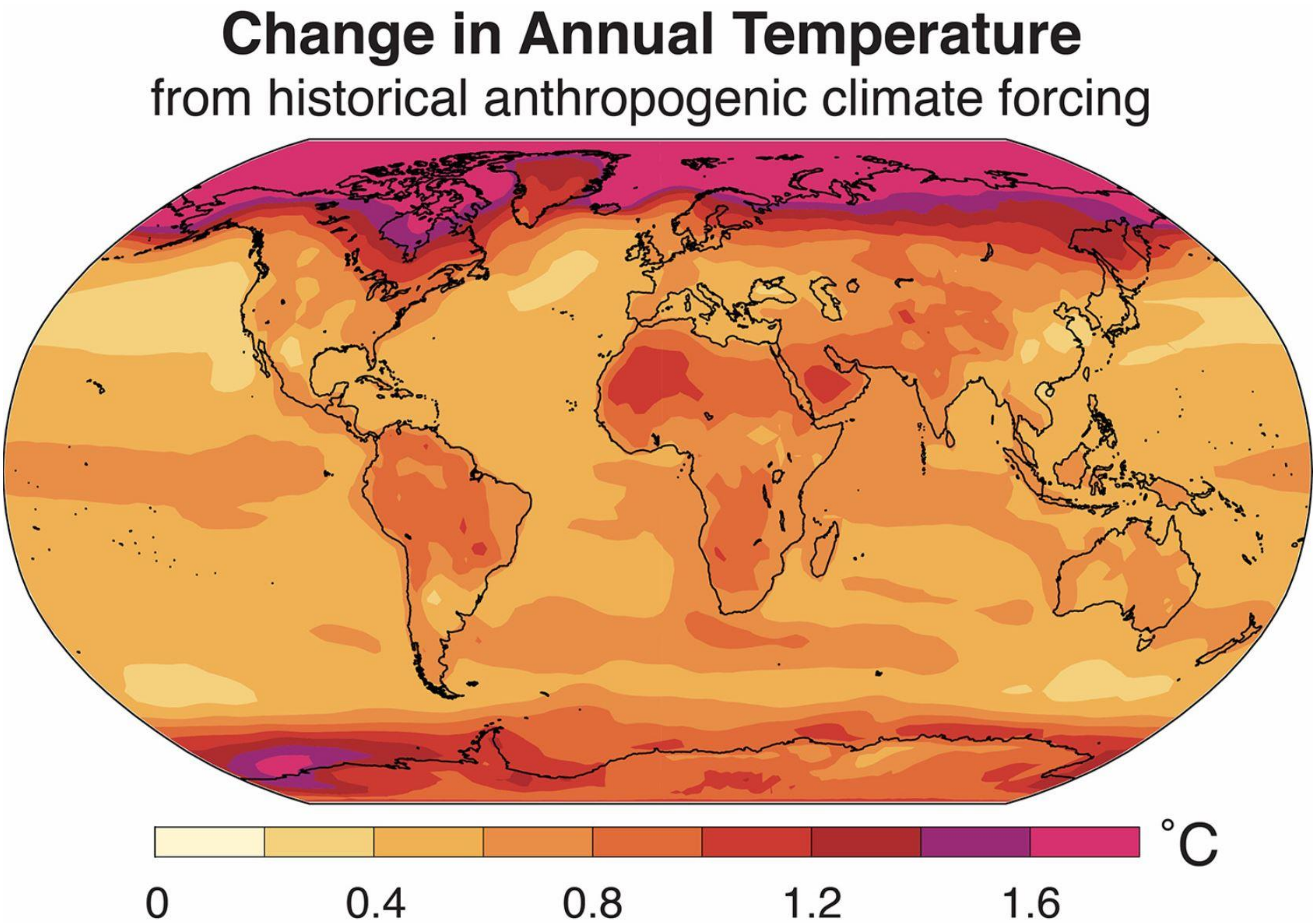
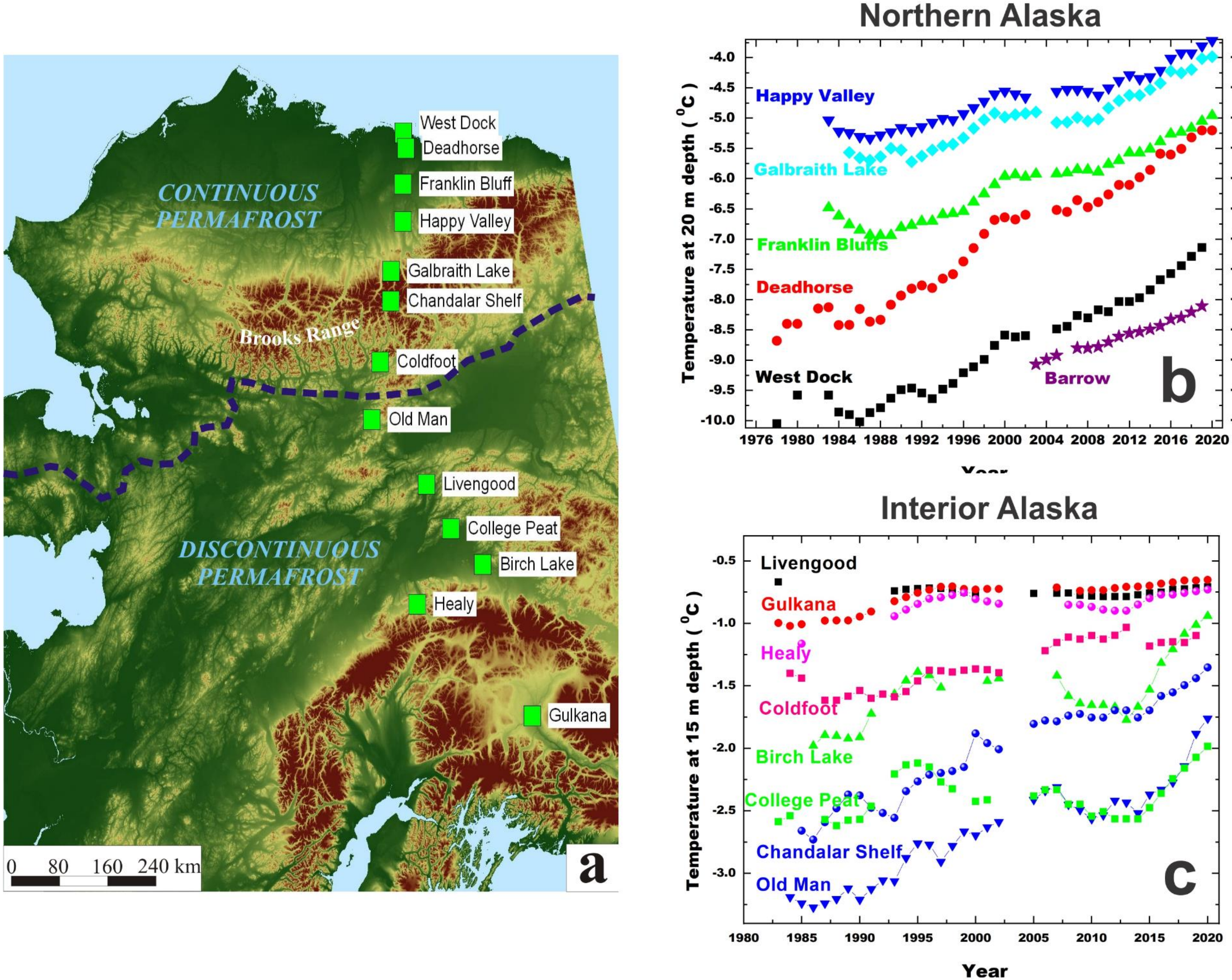
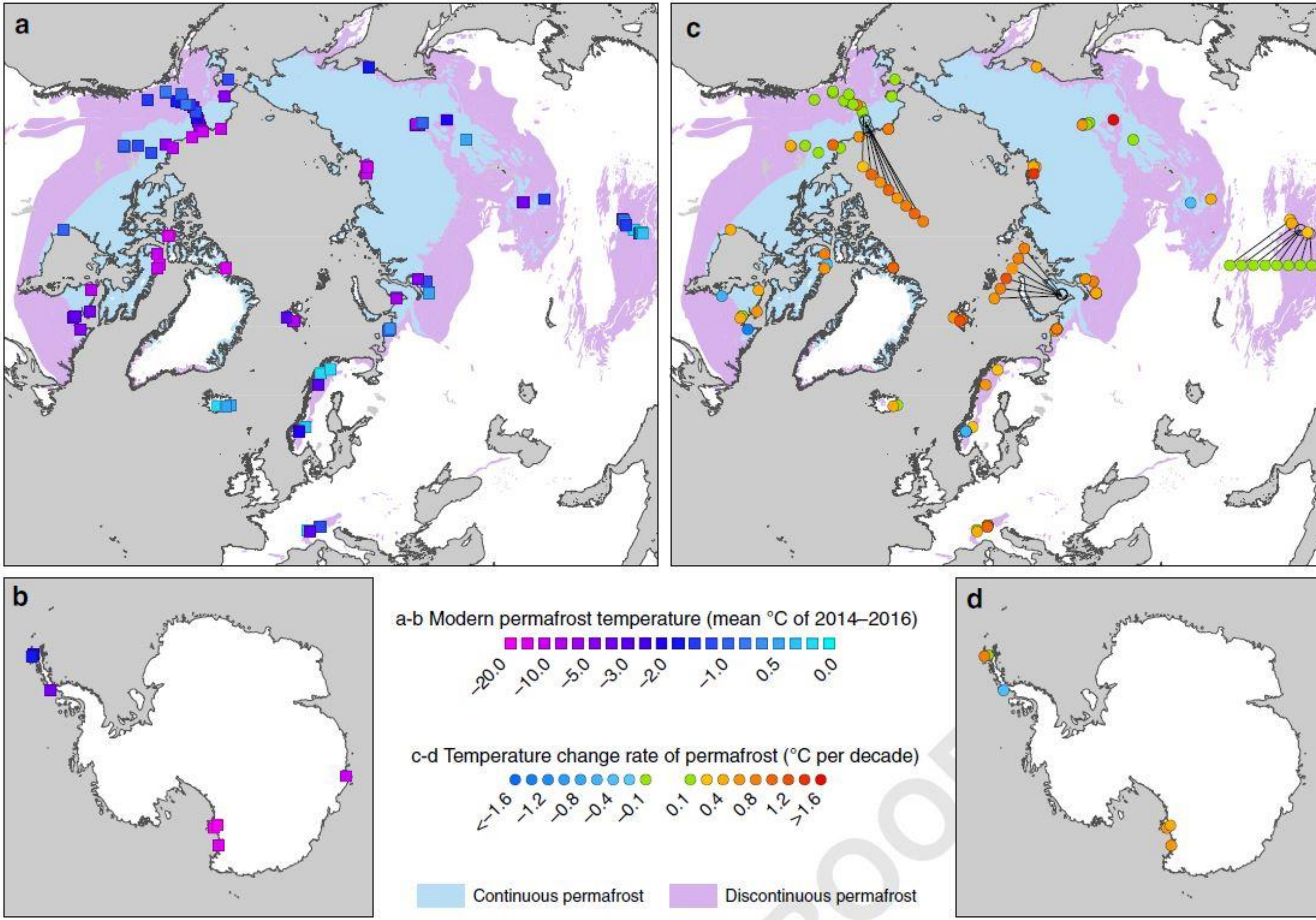


Image credit: Noah Diffenbaugh and Marshall Burke, 2018



West Dock
Deadhorse
Franklin Bluff
Happy Valley
CONTINUOUS PERMAFROST
Galbraith Lake
Chandalar Shelf
Brooks Range
Coldfoot
Old Man
Livengood
College Peat
Birch Lake
DISCONTINUOUS PERMAFROST
Healy
Gulkana
0 80 160 240 km
a
Northern Alaska
Temperature at 20 m depth (°C)
Happy Valley
Galbraith Lake
Franklin Bluffs
Deadhorse
West Dock
Barrow
b
Year
Interior Alaska
Temperature at 15 m depth (°C)
Livengood
Gulkana
Healy
Coldfoot
Birch Lake
College Peat
Chandalar Shelf
Old Man
c
Year

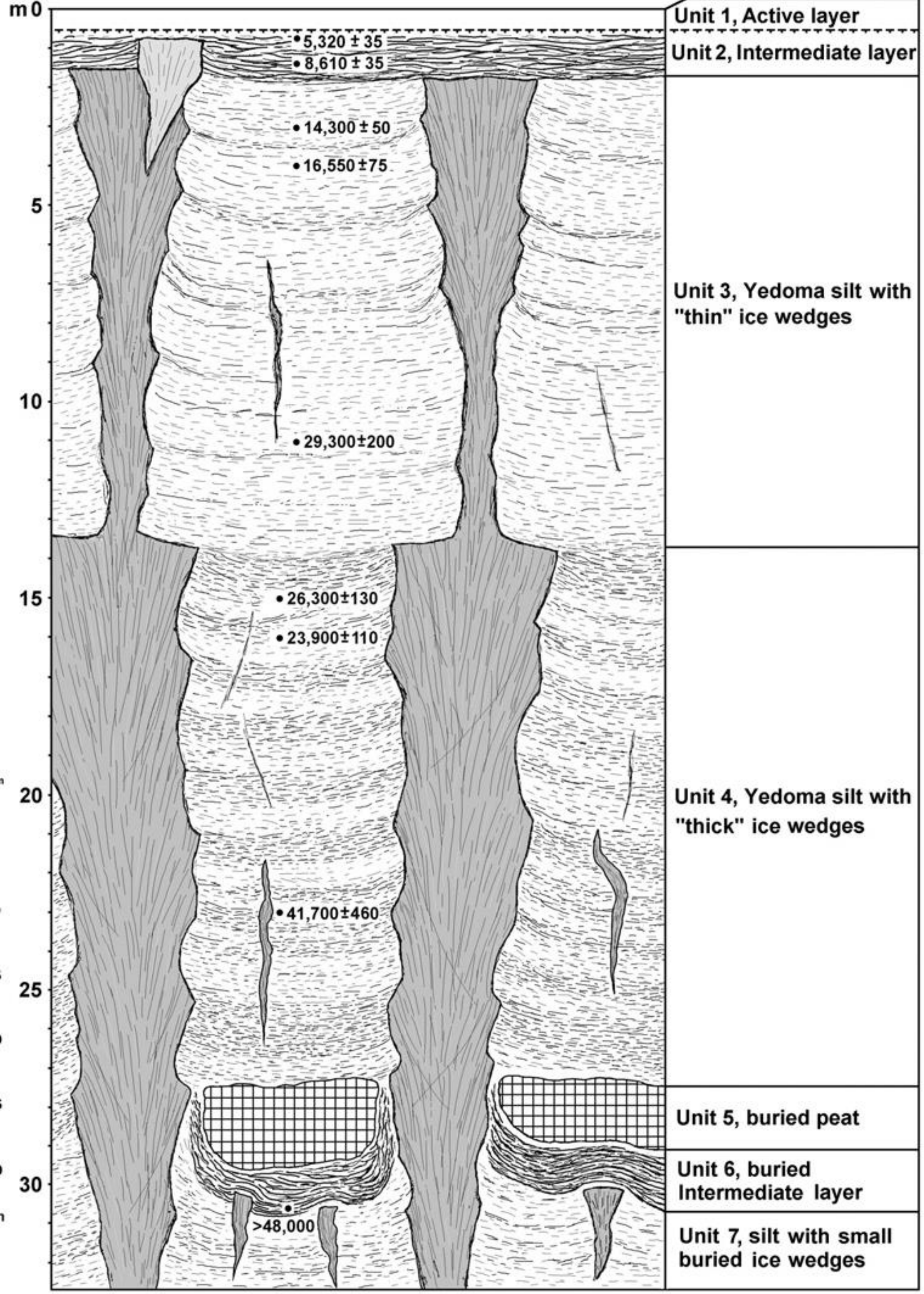


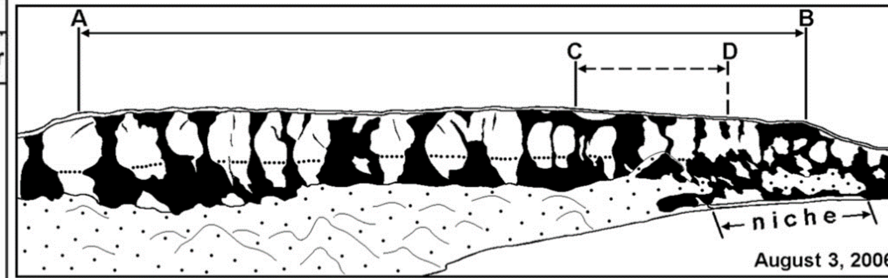
Biskaborn et al., 2017

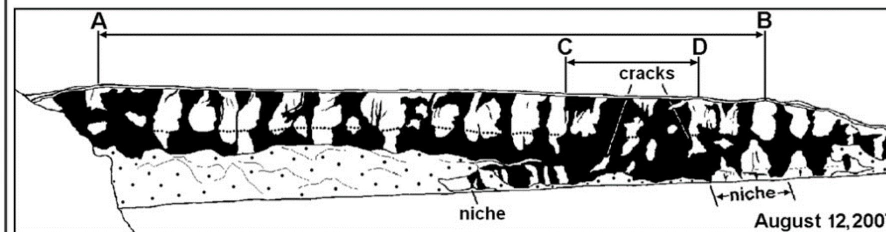
Distribution of Ice-Rich Yedoma (Ice Complex) Deposits in East Siberia

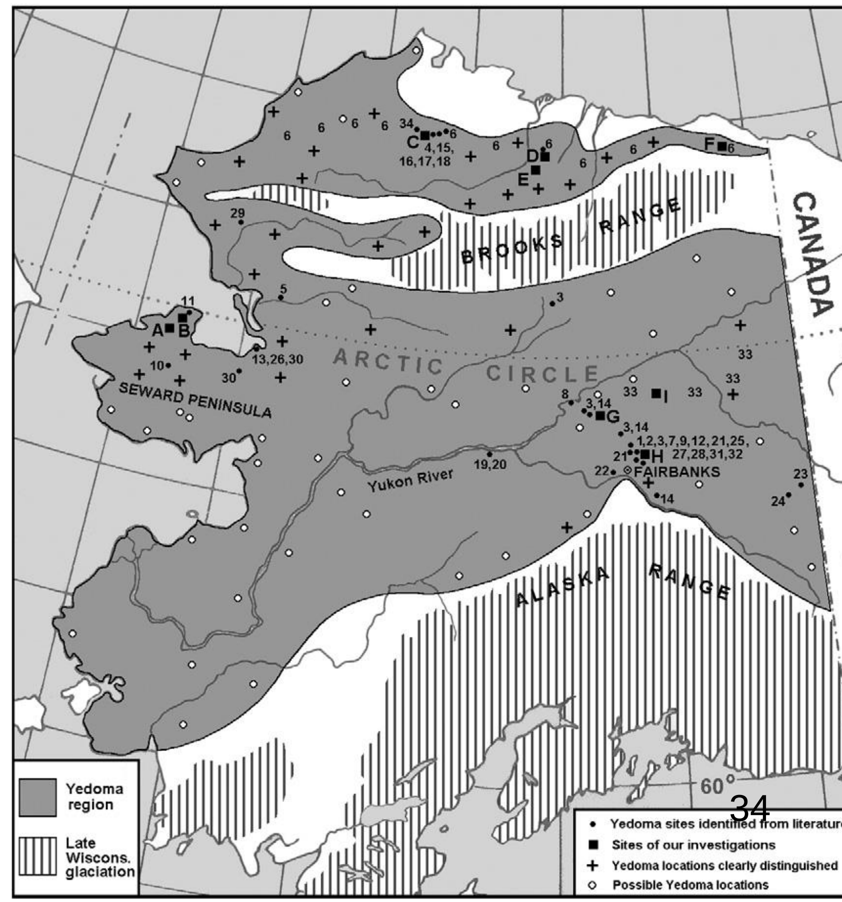
- *Thickness of the deposit is between 5-100m*
- *Present day total coverage is > 1x10^6 km*
- *Gravimetric ground ice contents in the sediments between 60-120%*
- *Including the ice wedges, total volumetric ice content of up to >75%*
- *Organic carbon content averages between 2-5%*
- *Accumulation during several 10 000 years*

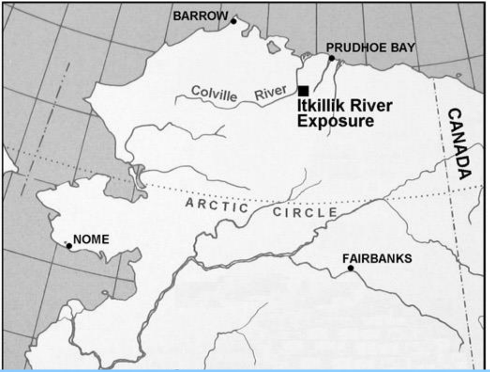
Zimov et al 2006 (Science), Schirrmeister et al., 2008


m 0
5
10
15
20
25
30
5,320 ± 35
8,610 ± 35
14,300 ± 50
16,550 ± 75
29,300±200
26,300±130
23,900±110
41,700±460
>48,000
Unit 1, Active layer
Unit 2, Intermediate layer
Unit 3, Yedoma silt with "thin" ice wedges
Unit 4, Yedoma silt with "thick" ice wedges
Unit 5, buried peat
Unit 6, buried Intermediate layer
Unit 7, silt with small buried ice wedges


A
B
C
D
niche
August 3, 2006

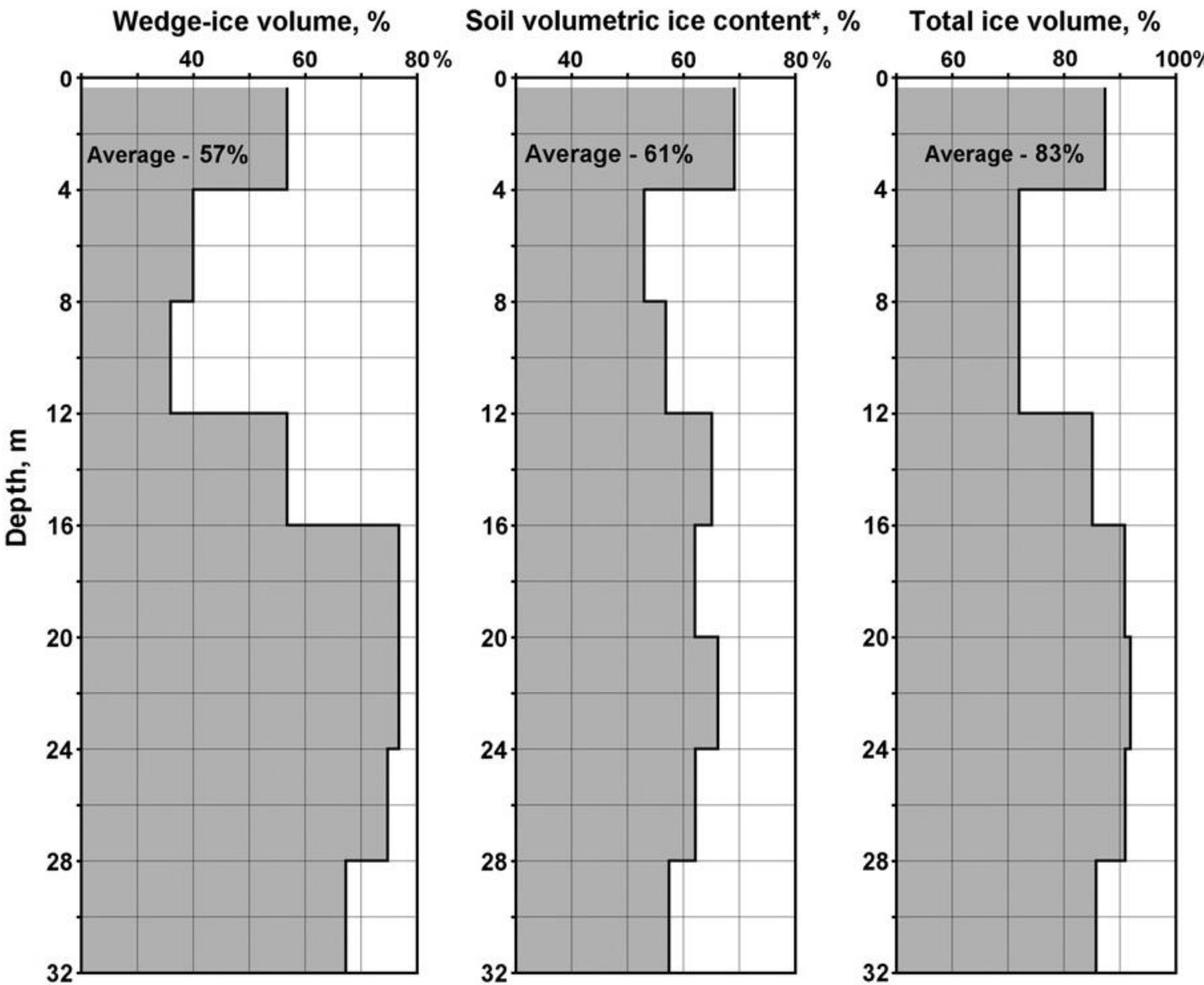

A
B
C
D
cracks
niche
niche
August 12,2007


BROOKS RANGE
CANADA
ARCTIC CIRCLE
SEWARD PENINSULA
Yukon River
FAIRBANKS
ALASKA RANGE
60°
Yedoma region
Late Wiscons. glaciation
Yedoma sites identified from literature
Sites of our investigations
Yedoma locations clearly distinguished
Possible Yedoma locations



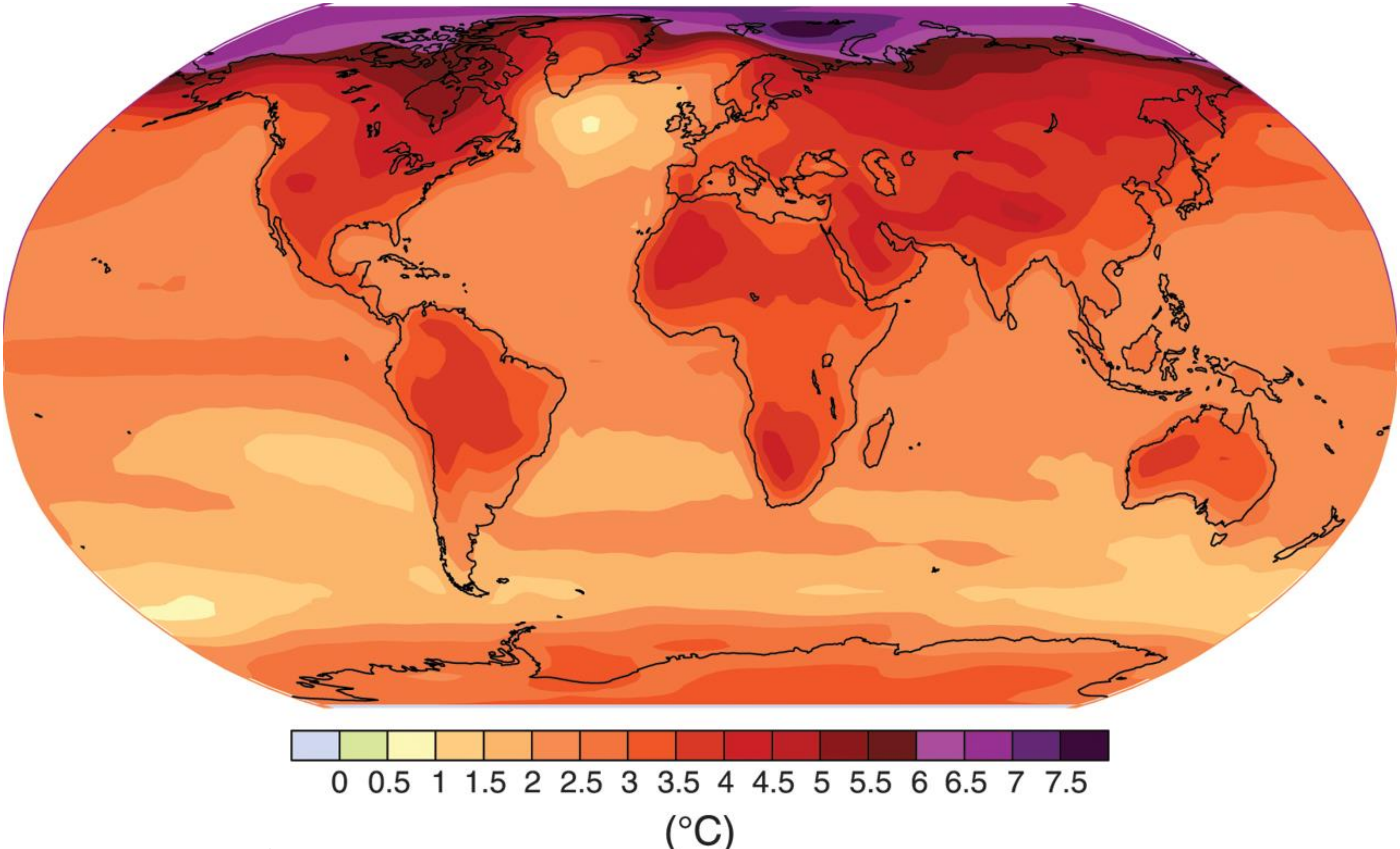
Cryostratigraphy of late Pleistocene syngenetic permafrost (yedoma) in northern Alaska, Itkillik River exposure

M. Kanevskiy [a,*], Y. Shur [a], D. Fortier [a,b], M.T. Jorgenson [a,c], E. Stephani [a]

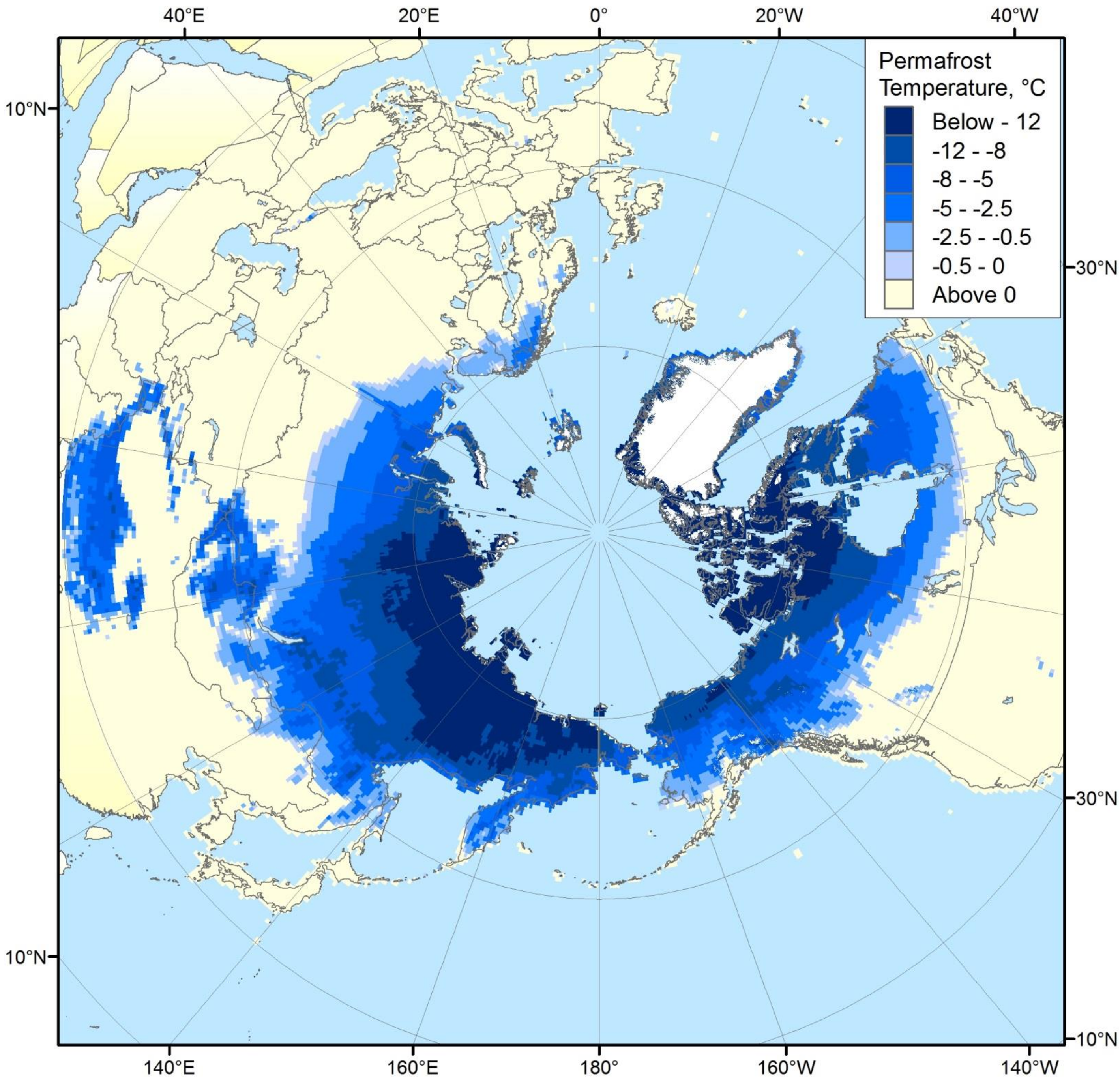


* due to segregated and pore ice

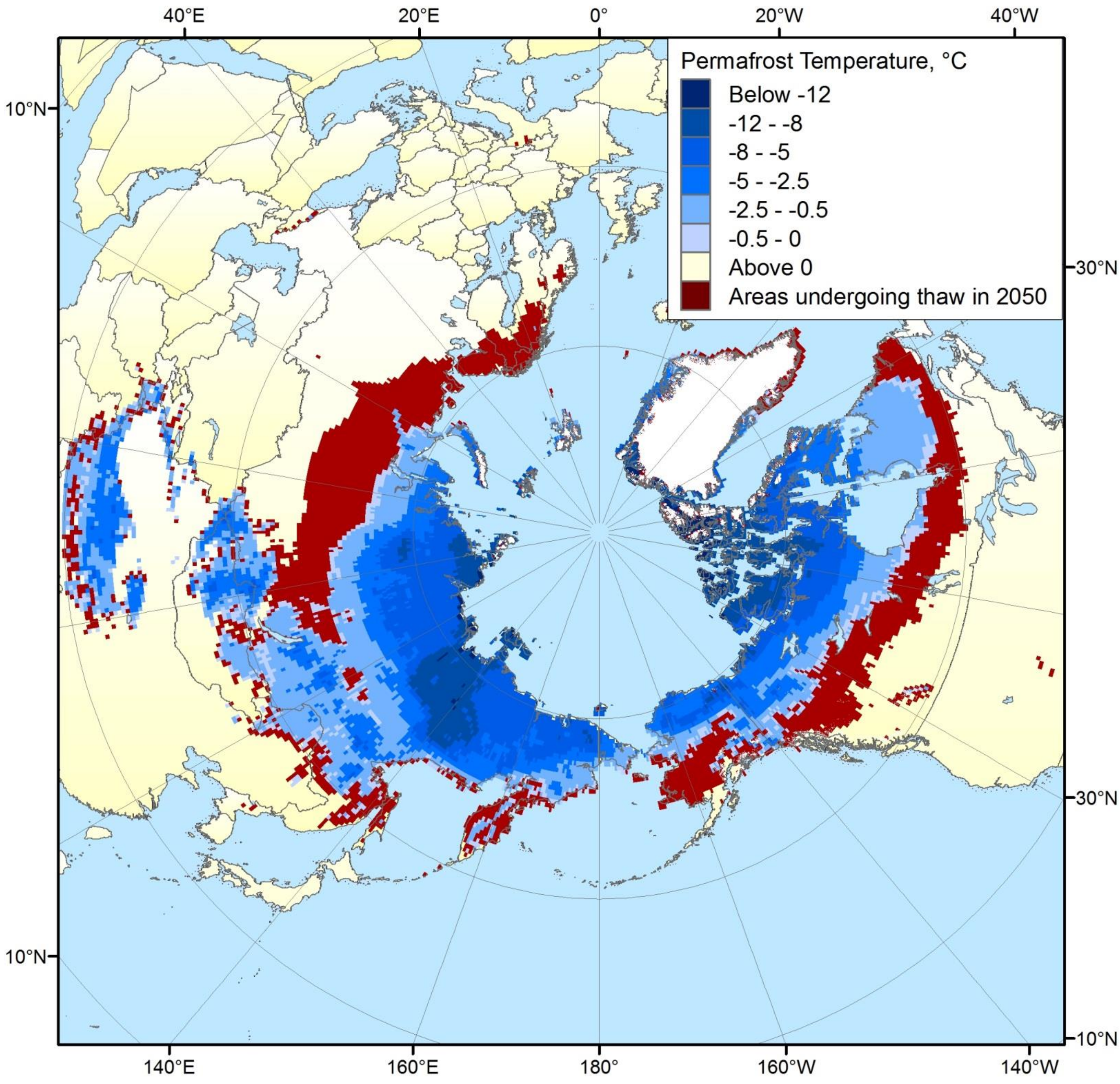
Projected surface air temperature (2090-2099 relative to 1980-1999)



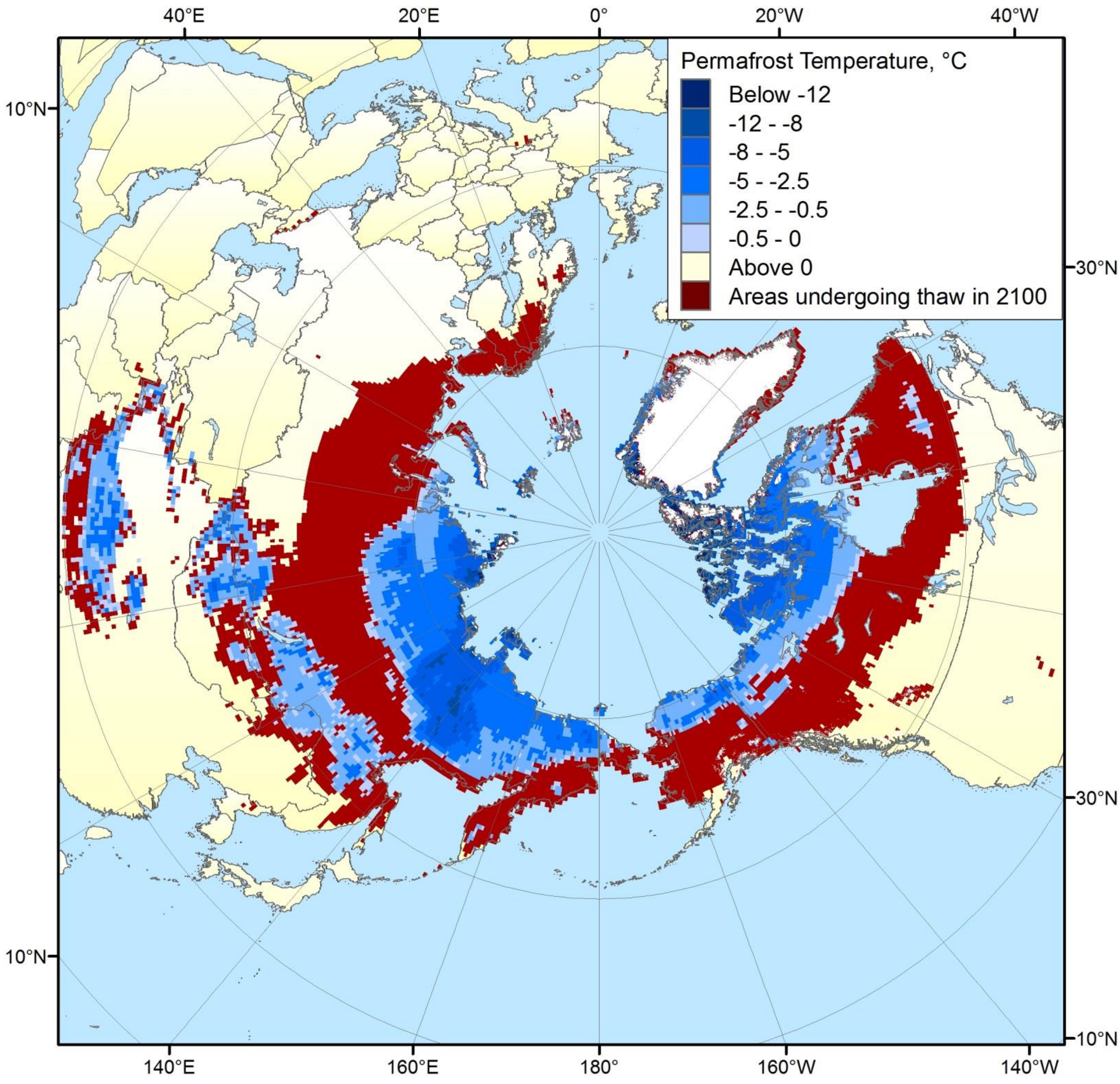
IPCC, 2007; Figure SPM6



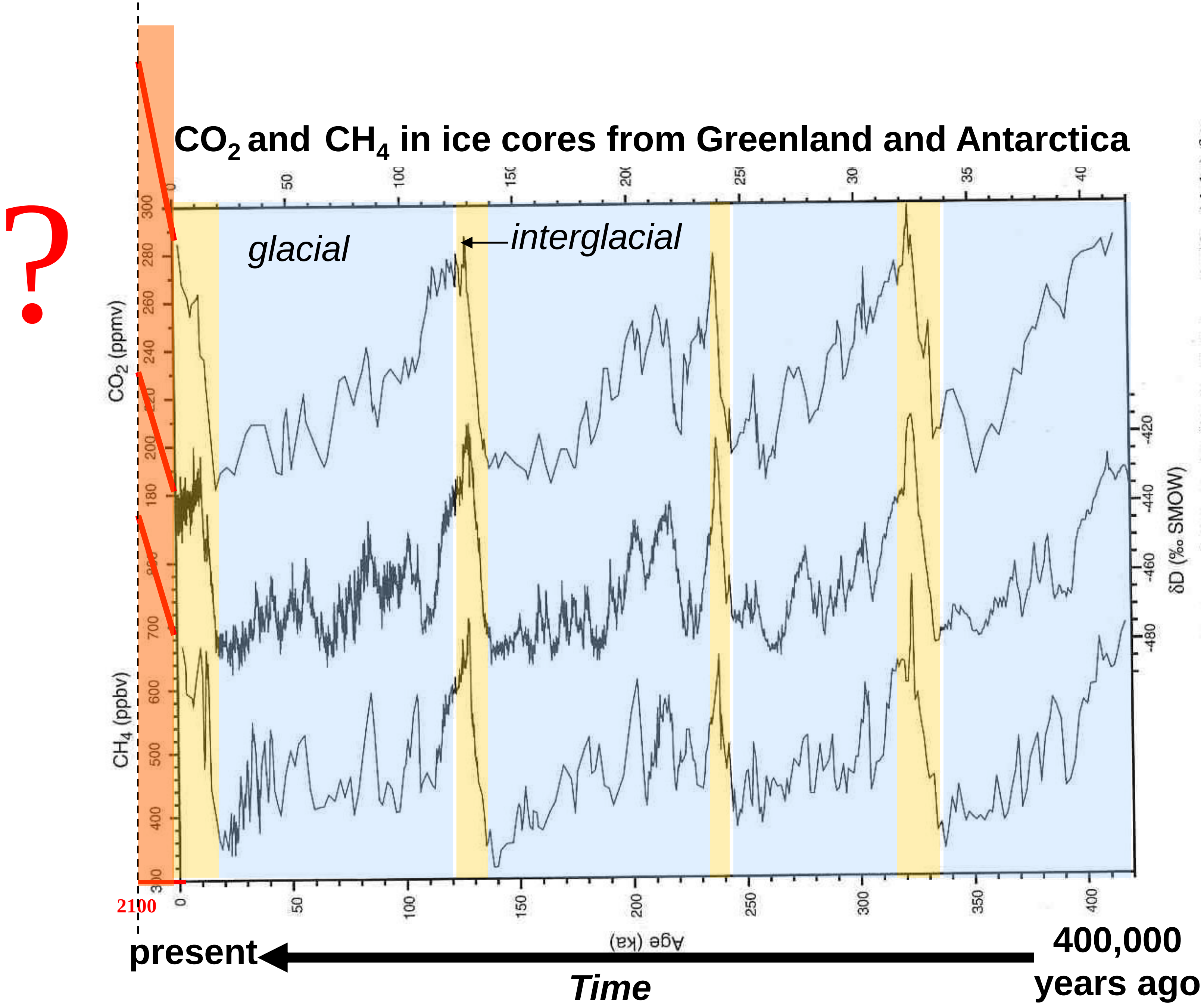
40°E
20°E
0°
20°W
40°W
10°N
30°N
30°N
10°N
10°N
140°E
160°E
180°
160°W
140°W
Permafrost Temperature, °C
Below - 12
-12 - -8
-8 - -5
-5 - -2.5
-2.5 - -0.5
-0.5 - 0
Above 0



40°E
20°E
0°
20°W
40°W
10°N
30°N
30°N
10°N
10°N
140°E
160°E
180°
160°W
140°W
Permafrost Temperature, °C
Below -12
-12 - -8
-8 - -5
-5 - -2.5
-2.5 - -0.5
-0.5 - 0
Above 0
Areas undergoing thaw in 2050



40°E
20°E
0°
20°W
40°W
10°N
30°N
30°N
10°N
10°N
140°E
160°E
180°
160°W
140°W
Permafrost Temperature, °C
Below -12
-12 - -8
-8 - -5
-5 - -2.5
-2.5 - -0.5
-0.5 - 0
Above 0
Areas undergoing thaw in 2100



CO2 and CH4 in ice cores from Greenland and Antarctica
?
glacial
interglacial
CO2 (ppmv)
CH4 (ppbv)
δD (‰ SMOW)
2100
present
Time
400,000 years ago

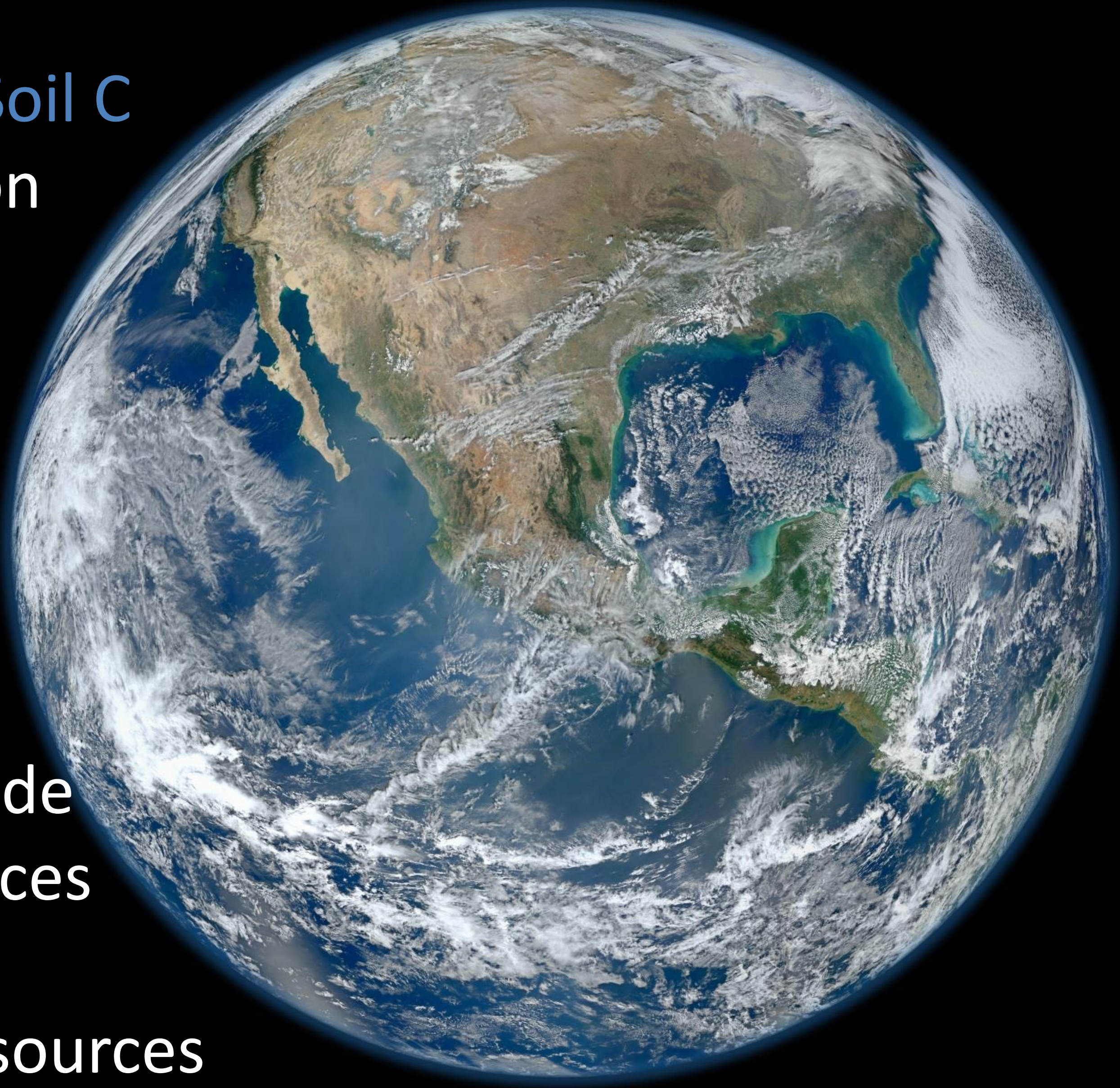
Permafrost Carbon Emissions

Permafrost Zone Soil C

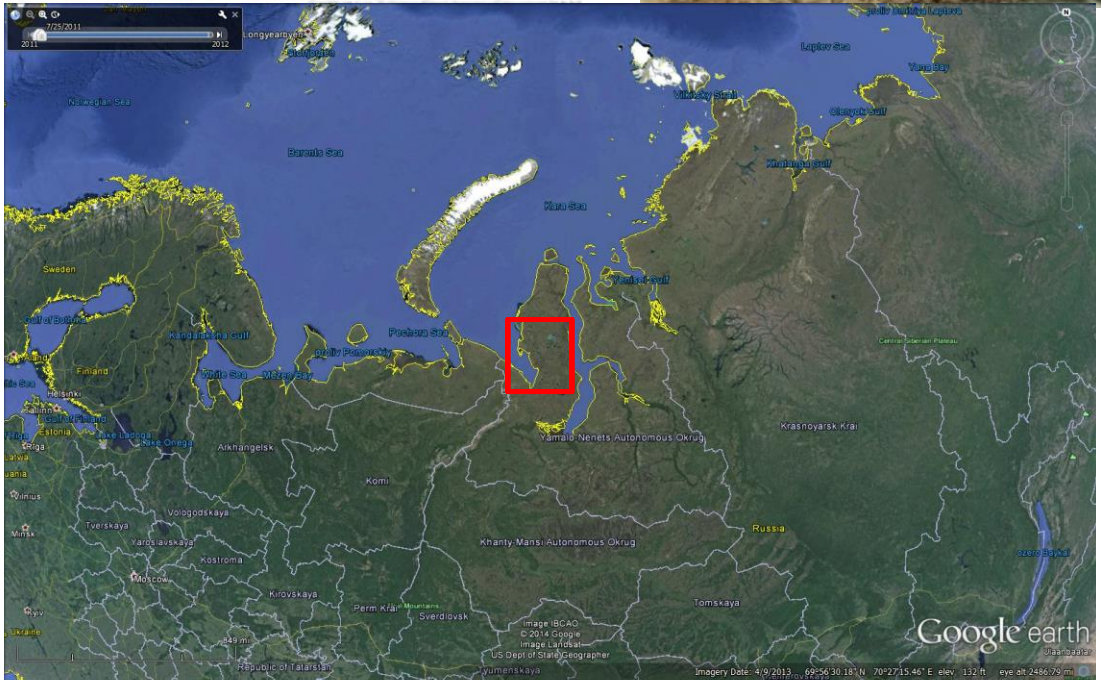
Vulnerable Fraction
~5-15% by 2100

10% of known
permafrost C pool
=130-160 Pg

Similar in magnitude
to biospheric sources
(land use change)
Less than human sources
(fossil fuel)



Schuur et al. 2015 Nature

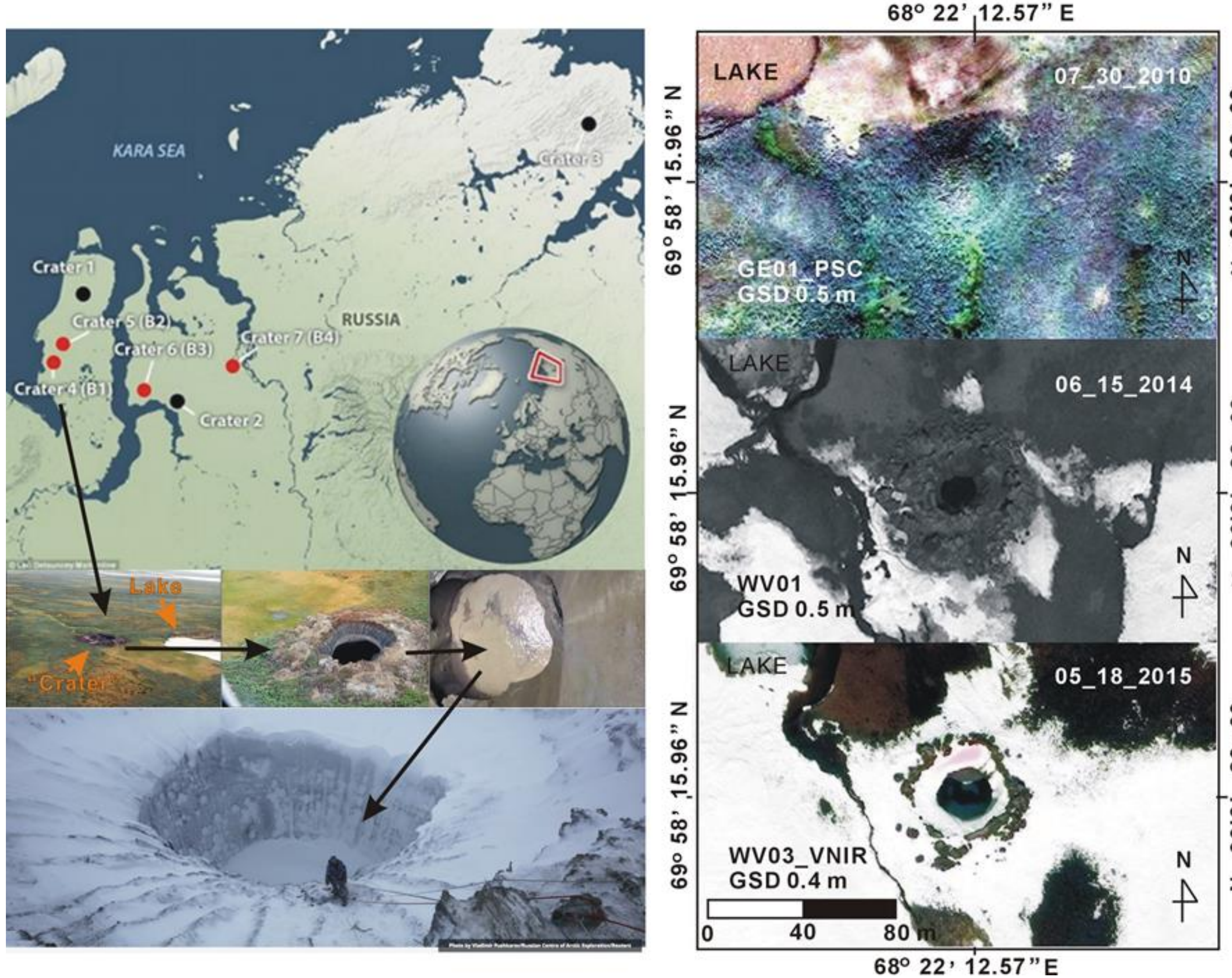


A Mysterious

Hole on Yamal

Peninsula

in Russia


KARA SEA
Crater 3
Crater 1
Crater 5 (B2)
Crater 6 (B3)
Crater 7 (B4)
RUSSIA
Crater 4 (B1)
Crater 2
Lake
"Crater"
68° 22' 12.57" E
LAKE
07_30_2010
GE01_PSC
GSD 0.5 m
69° 58' 15.96" N
LAKE
06_15_2014
WV01
GSD 0.5 m
LAKE
05_18_2015
WV03_VNIR
GSD 0.4 m
0
40
80 m
N
68° 22' 12.57" E

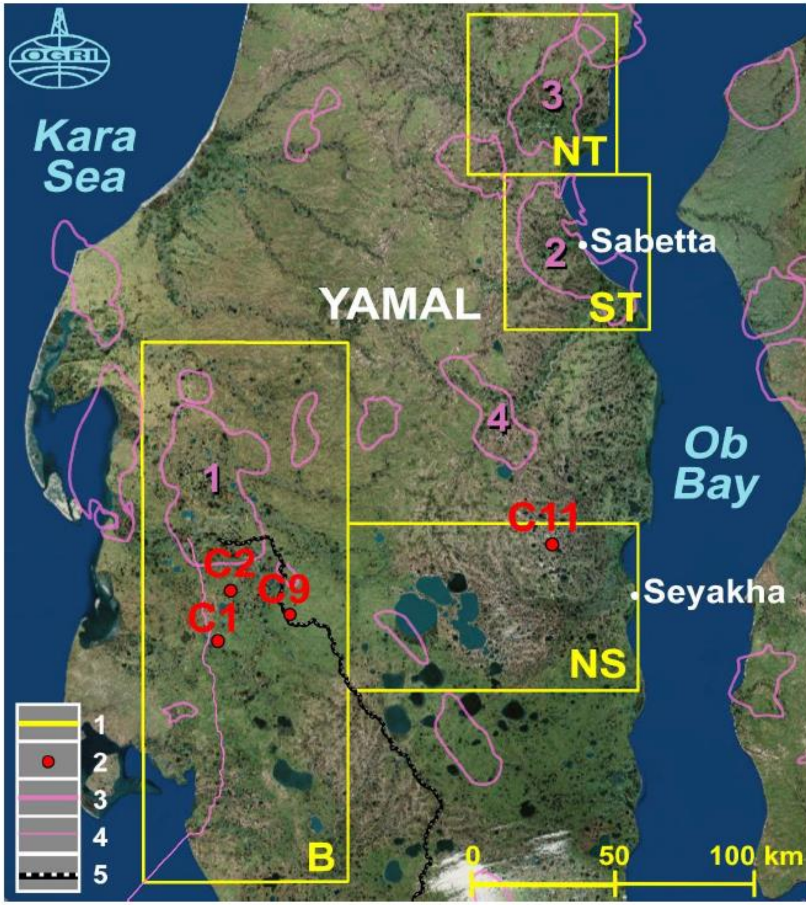


Figure 1. Gas blowout craters in the central part of the Yamal Peninsula. (1) Areas of detailed studies of Oil and Gas Research Institute of Russian Academy of Sciences (OGRI RAS): B, Bovanenkovo; ST, South Tambey; NT, North Tambey; NS, Neito-Seyakha. (2) Craters of gas blowouts C1, C2, C9 and C11. (3) Gas and gas condensate fields including those marked with pink color: Bovanenkovo (1), South Tambey (2), North Tambey (3) and West Seyakha (4). (4) Gas pipeline Bovanenkovo-Ukhta. (5) Railroad. Basemap—ESRI standard imagery.

V.Bogoyavlensky, 2020

Рис. 6. Термокарстовое озеро с кратерами выбросов газа в северо-восточной части Ямала (фото В. И. Богоявленского из вертолета 15 июля 2015 г.)
Fig. 6. Thermokarst lake with gas blowout craters in the north-eastern part of Yamal (photo by V. I. Bogoyavlensky from a helicopter on July 15, 2015)

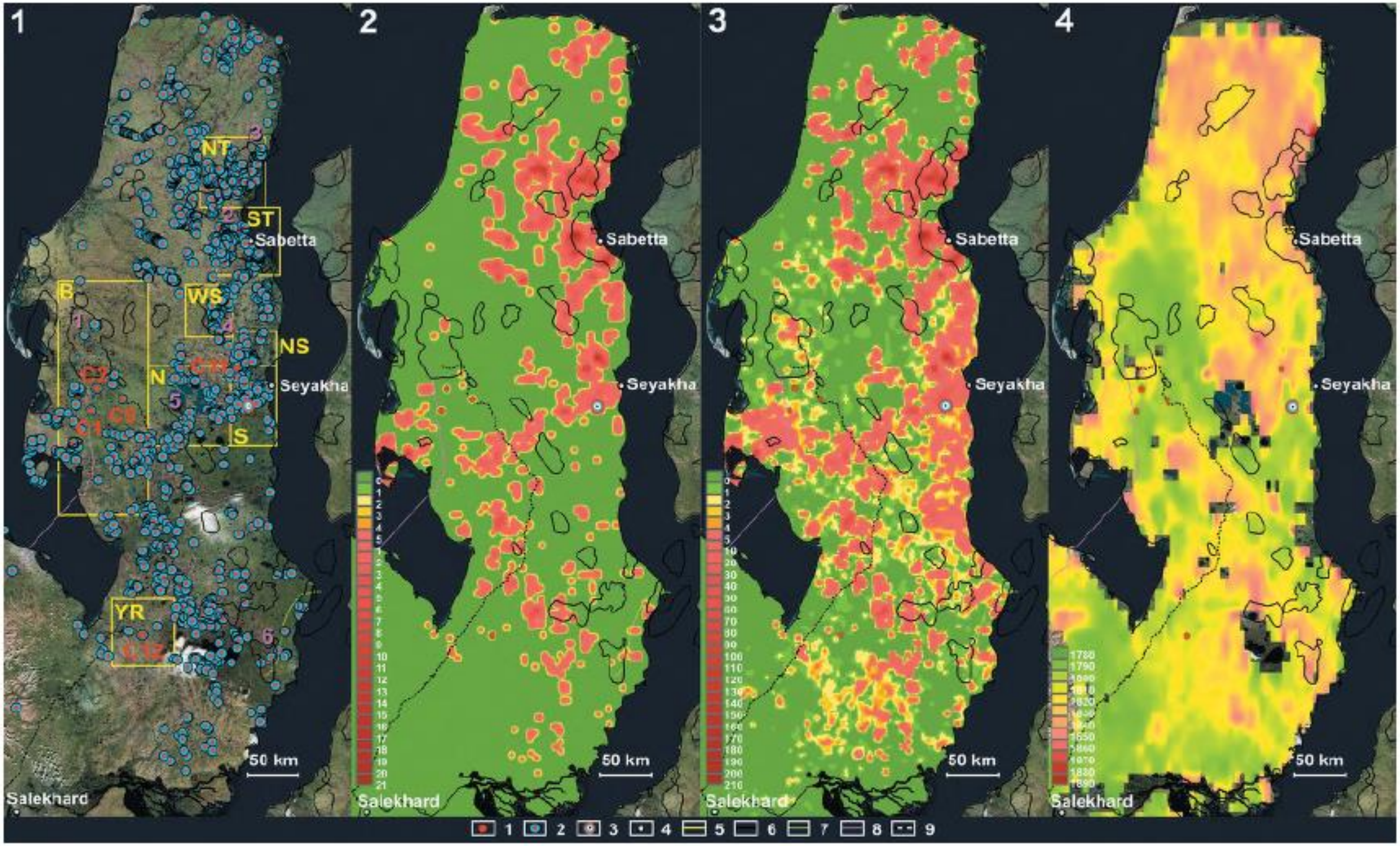


Рис. 8. Схемы распространения кратеров выбросов газа на суше полуострова Ямал и зон дегазации из термокарстовых озер с кратерами на дне (1), плотности распространения зон дегазации из озер с кратерами на дне (2), условного риска мощных выбросов газа (3) и распределение концентрации метана по данным спектрометра TROPOMI спутника Sentinel-5P (4). Обозначения: 1 – кратеры выбросов газа C1, C2, C9, C11 и C12; 2 – озера с кратерами на дне; 3 – озеро Открытие; 4 – населенные пункты; 5 – участки детальных исследований (B – Бованенковский, ST – Южно-Тамбейский, NT – Северо-Тамбейский, N – Нейтинский, S – Сеяхинский, NS – Северо-Сеяхинский, WS – Западно-Сеяхинский, YR – Еркутинский); 6 – месторождения углеводородов, включая показанные цифрами Бованенковское (1), Южно-Тамбейское (2), Северо-Тамбейское (3), Западно-Сеяхинское (4), Нейтинское (5) и Новопортовское (6); 7 – нефтепровод; 8 – газопровод Бованенково-Ухта; 9 – железная дорога. Картографическая основа – ESRI


Thank you very much !
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