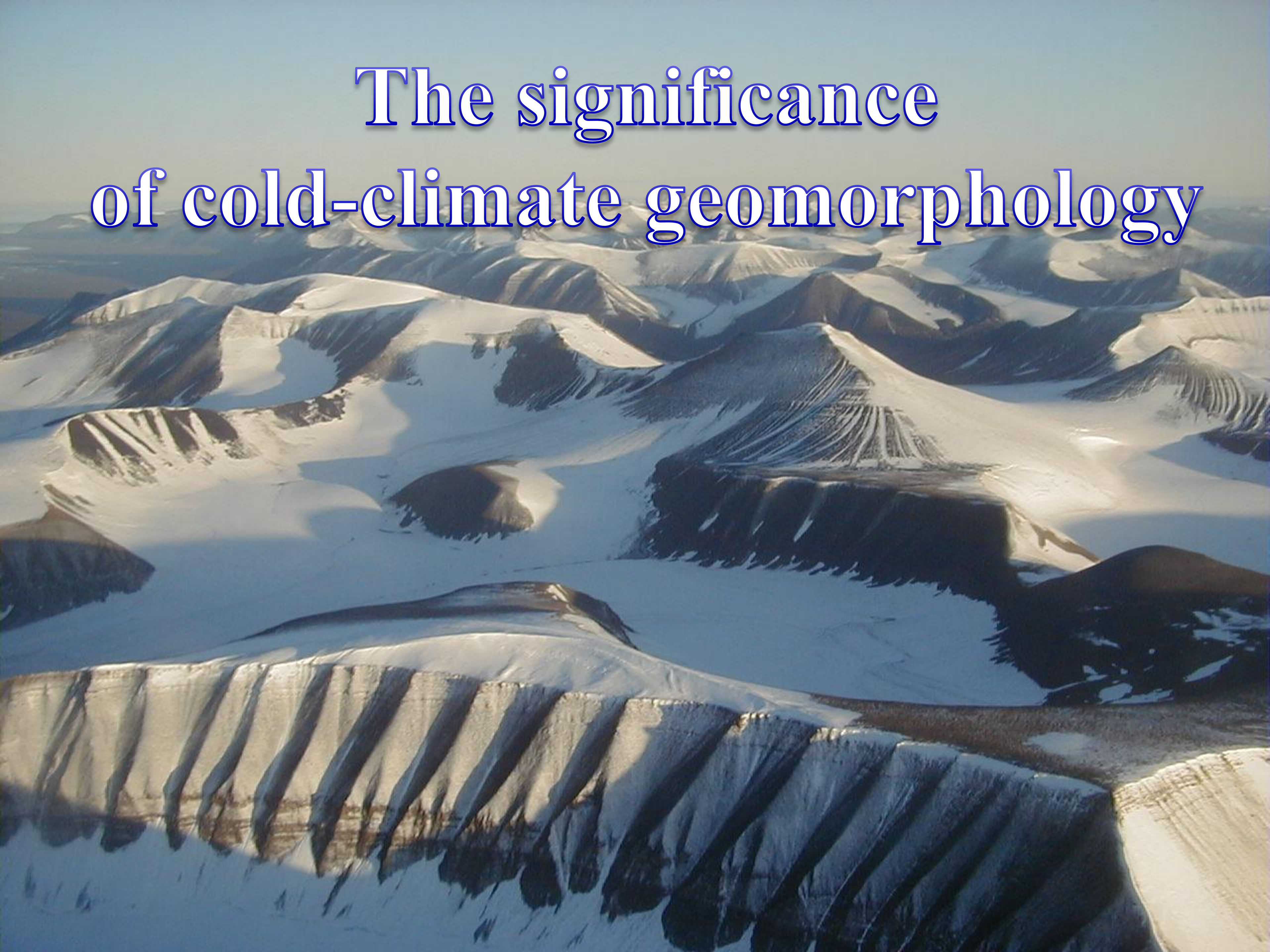
The significance of cold-climate geomorphology



The significance of cold-climate geomorphology

1: Why interest in cold-climate geomorphology ?

2: Glaciation

3: Periglaciation

4: Permafrost

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articles

Increased sedimentation rates and grain sizes 2–4 Myr ago due to the influence of climate change on erosion rates

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Around the globe, and in a variety of settings including active and inactive mountain belts, increases in sedimentation rates as well as in grain sizes of sediments were recorded at ~2–4 Myr ago, implying increased erosion rates. A change in climate represents the only process that is globally synchronous and can potentially account for the widespread increase in erosion and sedimentation, but no single process—like a lowering of sea levels or expanded glaciation—can explain increases in sedimentation in all environments, encompassing continental margins and interiors, and tropical as well as higher latitudes. We suggest that climate affected erosion mainly by the transition from a period of climate stability, in which landscapes had attained equilibrium configurations, to a time of frequent and abrupt changes in temperature, precipitation and vegetation, which prevented fluvial and glacial systems from establishing equilibrium states.

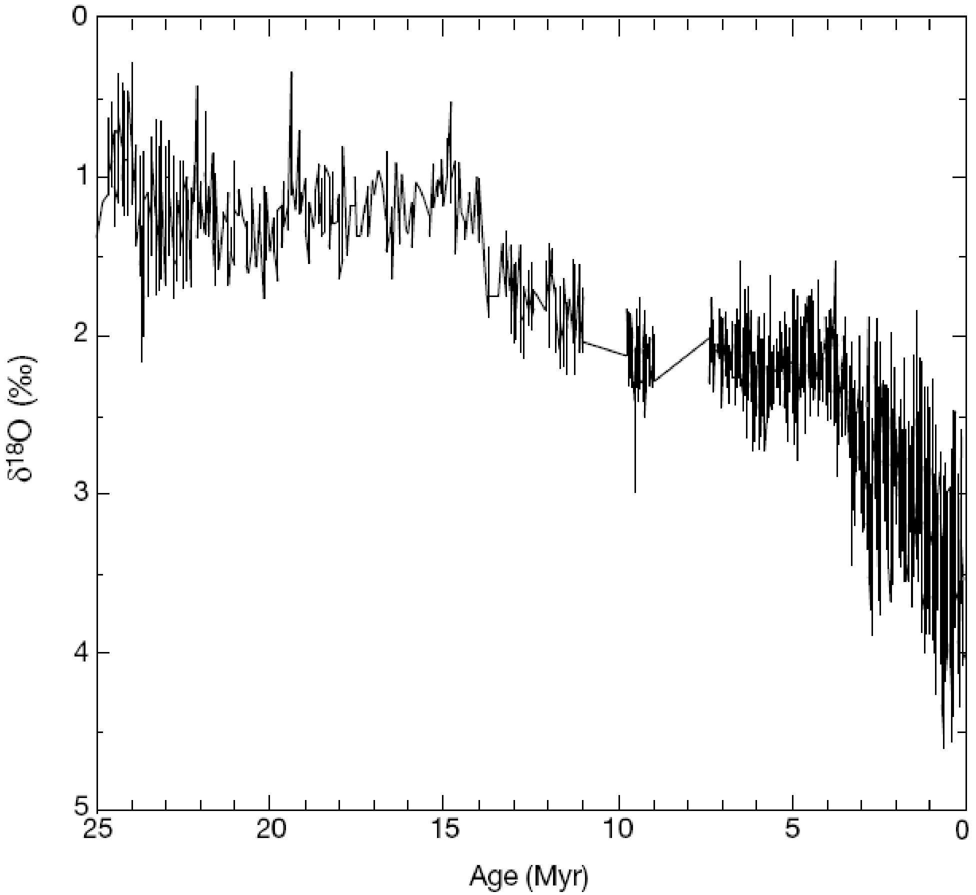
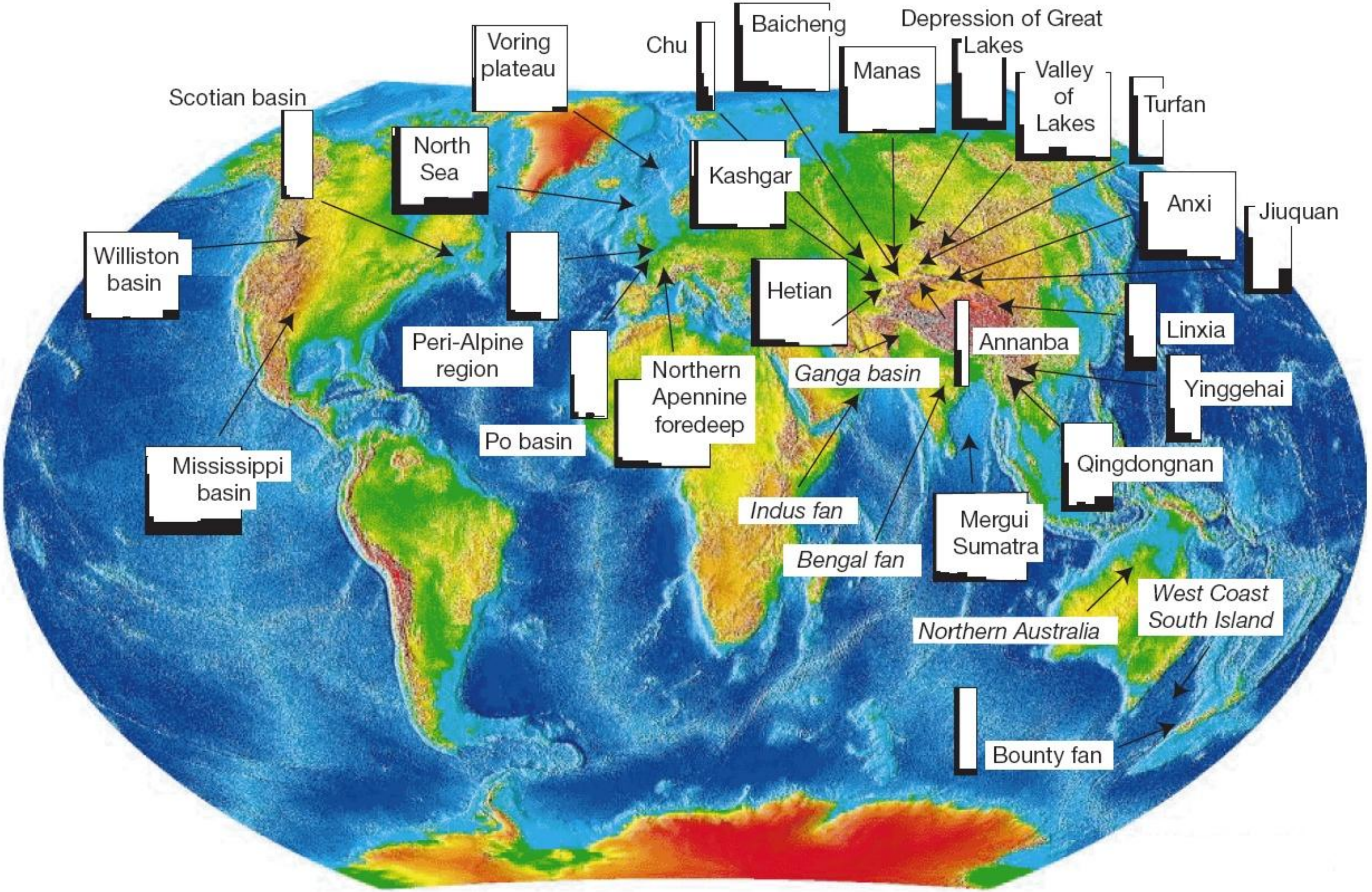


Figure 1 Plot of $\delta^{18}O$ from benthic foraminifers since 25 Myr ago, showing increases in mean values and in variability since ~4 Myr ago. The former increases imply cooling, and the latter increases imply an increasingly variable climate. Values (in ‰) have been measured largely (~95%) from fossil tests of *Cibicoides* spp., or adjusted to be equivalent to those of *Cibicoides* (ref. 63), from the Ceara rise in the eastern equatorial Atlantic Ocean (Ocean Drilling Project sites 925, 926 and 926). Values are plotted increasing downwards to reflect cooling. Data are from refs 62–66, and from T. Bickert and W. B. Curry, personal communication.


Voring plateau
Chu
Baicheng
Depression of Great Lakes
Manas
Valley of Lakes
Turfan
Scotian basin
North Sea
Kashgar
Anxi
Jiuquan
Williston basin
Peri-Alpine region
Hetian
Linxia
Annanba
Northern Apennine foredeep
Ganga basin
Yinggehai
Po basin
Mississippi basin
Qingdongnan
Indus fan
Mergui Sumatra
Bengal fan
West Coast South Island
Northern Australia
Bounty fan

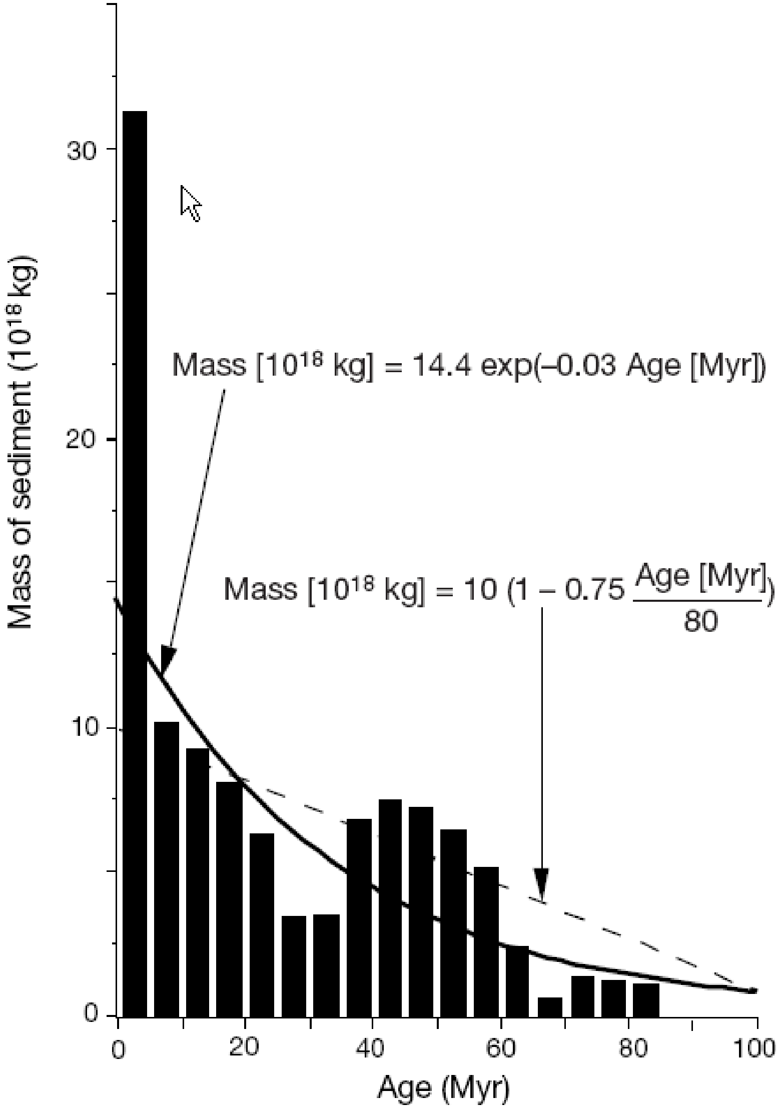
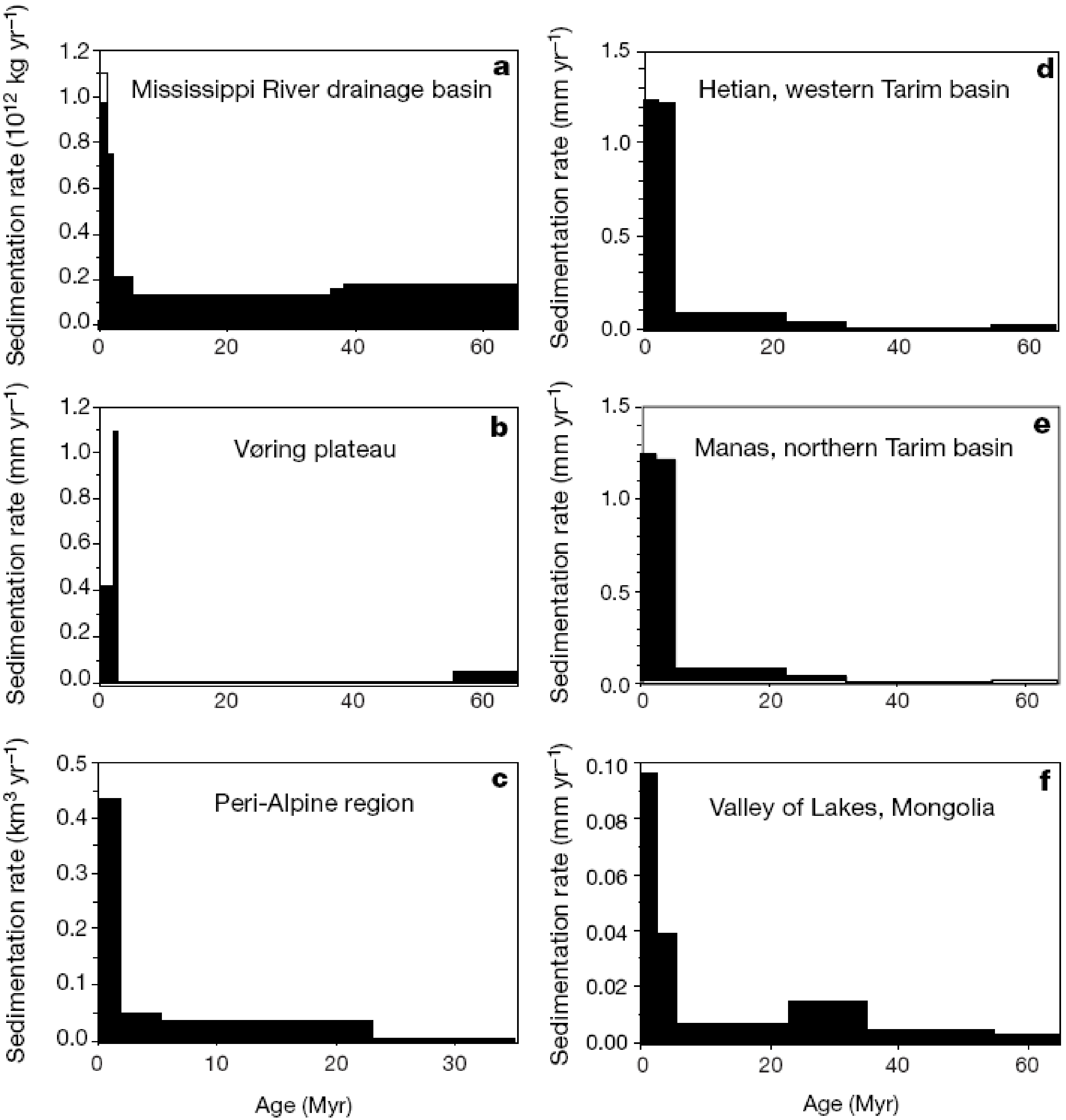


Figure 3 Histogram of terrigenous sediment deposited in the world's oceans, compiled by Hay *et al.*[6]. We note the abrupt increase since ~5 Myr ago. The solid curve is an exponential fit to the data; it deviates markedly from the sedimentation rate since 5 Myr ago. The global sea floor contains nearly all the floor created in the past 5 Myr but only a


a
Mississippi River drainage basin
Sedimentation rate (10^{12} kg yr^{-1})
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
20
40
60
b
Vøring plateau
Sedimentation rate (mm yr^{-1})
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
20
40
60
c
Peri-Alpine region
Sedimentation rate (km^3 yr^{-1})
0.0
0.1
0.2
0.3
0.4
0.5
0
10
20
30
Age (Myr)
d
Hetian, western Tarim basin
Sedimentation rate (mm yr^{-1})
0.0
0.5
1.0
1.5
0
20
40
60
e
Manas, northern Tarim basin
Sedimentation rate (mm yr^{-1})
0.0
0.5
1.0
1.5
0
20
40
60
f
Valley of Lakes, Mongolia
Sedimentation rate (mm yr^{-1})
0.00
0.02
0.04
0.06
0.08
0.10
0
20
40
60
Age (Myr)

may incise and denude surfaces more rapidly than would equable climates climate of any kind alone, even if erosion has occurred during only part of the past few million years. We consider that the increased sedimentation of coarser material since 2–4 Myr ago may have been caused by a climate shift. This shift was from a relatively unvarying climate, to one that oscillated between states that prepared the surface during some periods—by chemical weathering, periglacial fracturing, or other forms of mass wasting—and states that transported material.

Received 5 September 2000; accepted 2 March 2001.

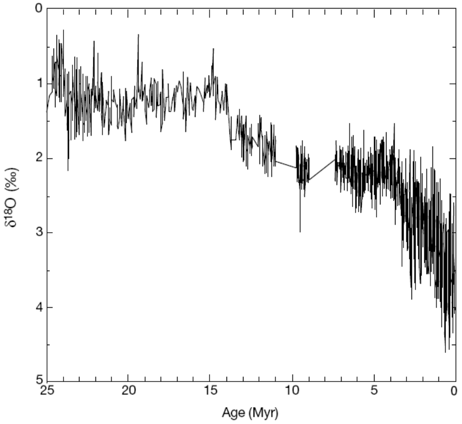
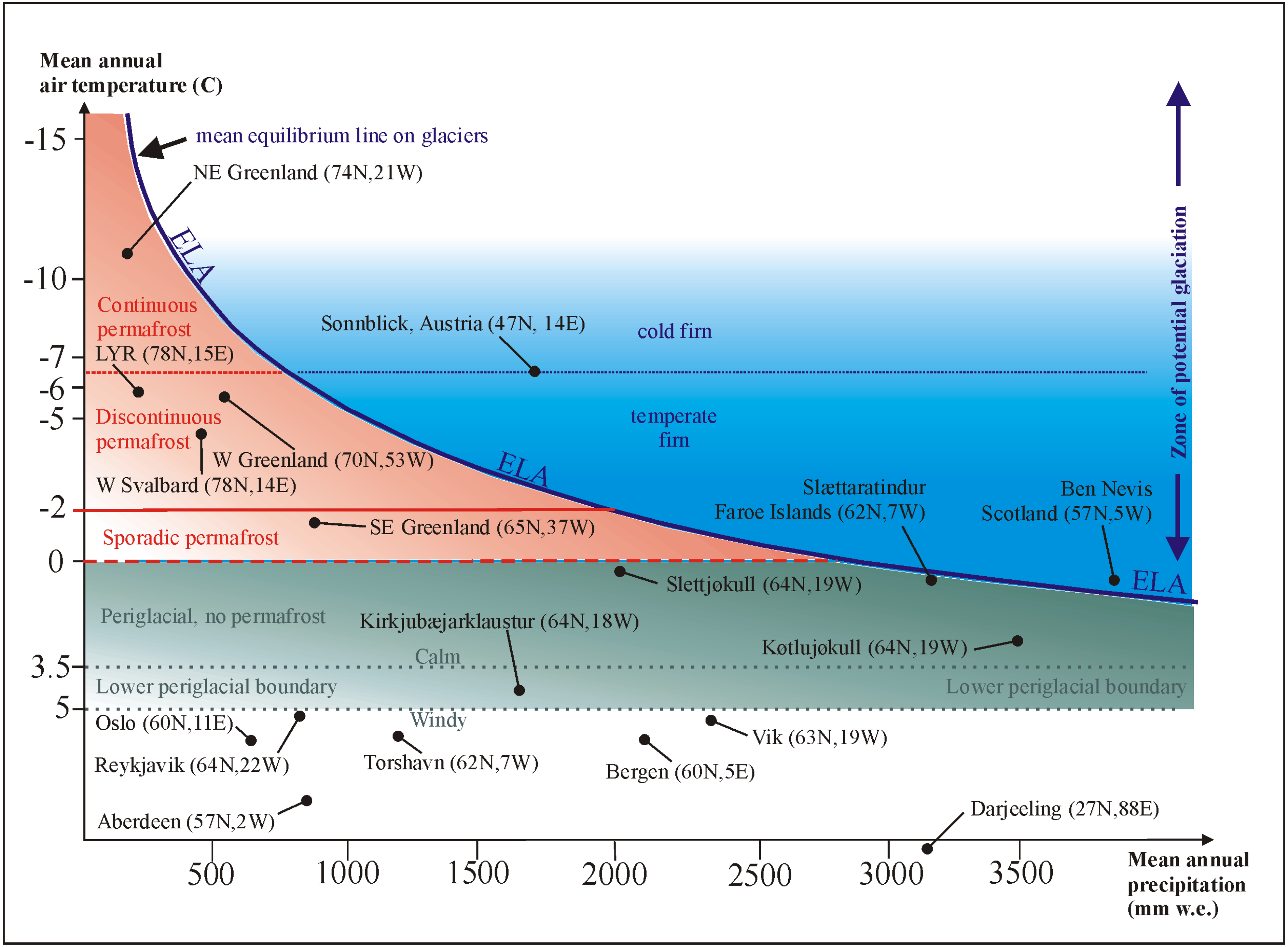


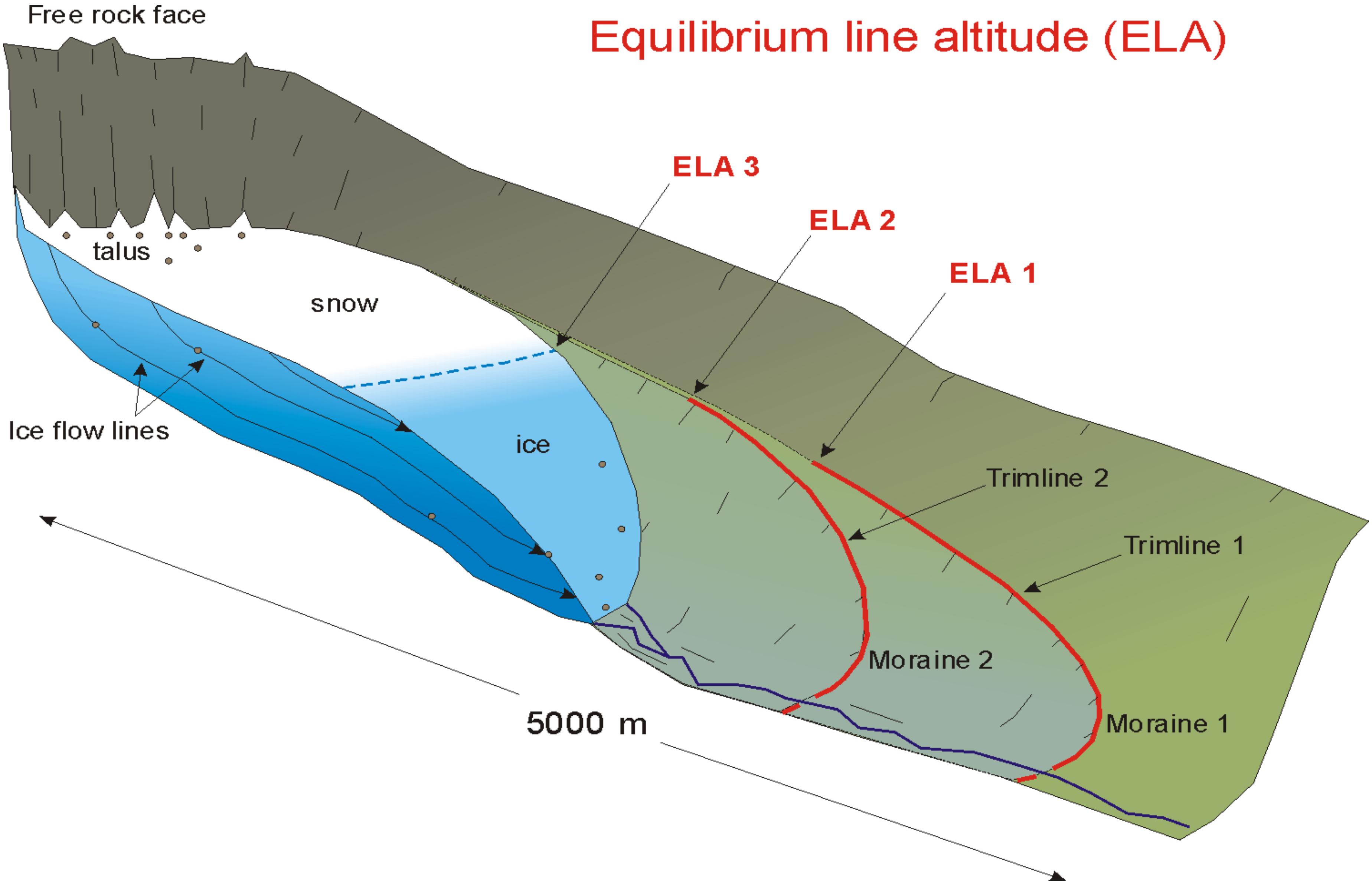
Figure 1 Plot of $\delta^{18}O$ from benthic foraminifers since 25 Myr ago, showing increases in mean values and in variability since ~4 Myr ago. The former increases imply cooling, and the latter increases imply an increasingly variable climate. Values (in ‰) have been measured largely (~95%) from fossil tests of *Cibicoides* spp., or adjusted to be equivalent to those of *Cibicoides* (ref. 63), from the Ceara rise in the eastern equatorial Atlantic Ocean (Ocean Drilling Project sites 925, 926 and 926). Values are plotted increasing downwards to reflect cooling. Data are from refs 62–66, and from T. Bickert and W. B. Curry, personal communication.

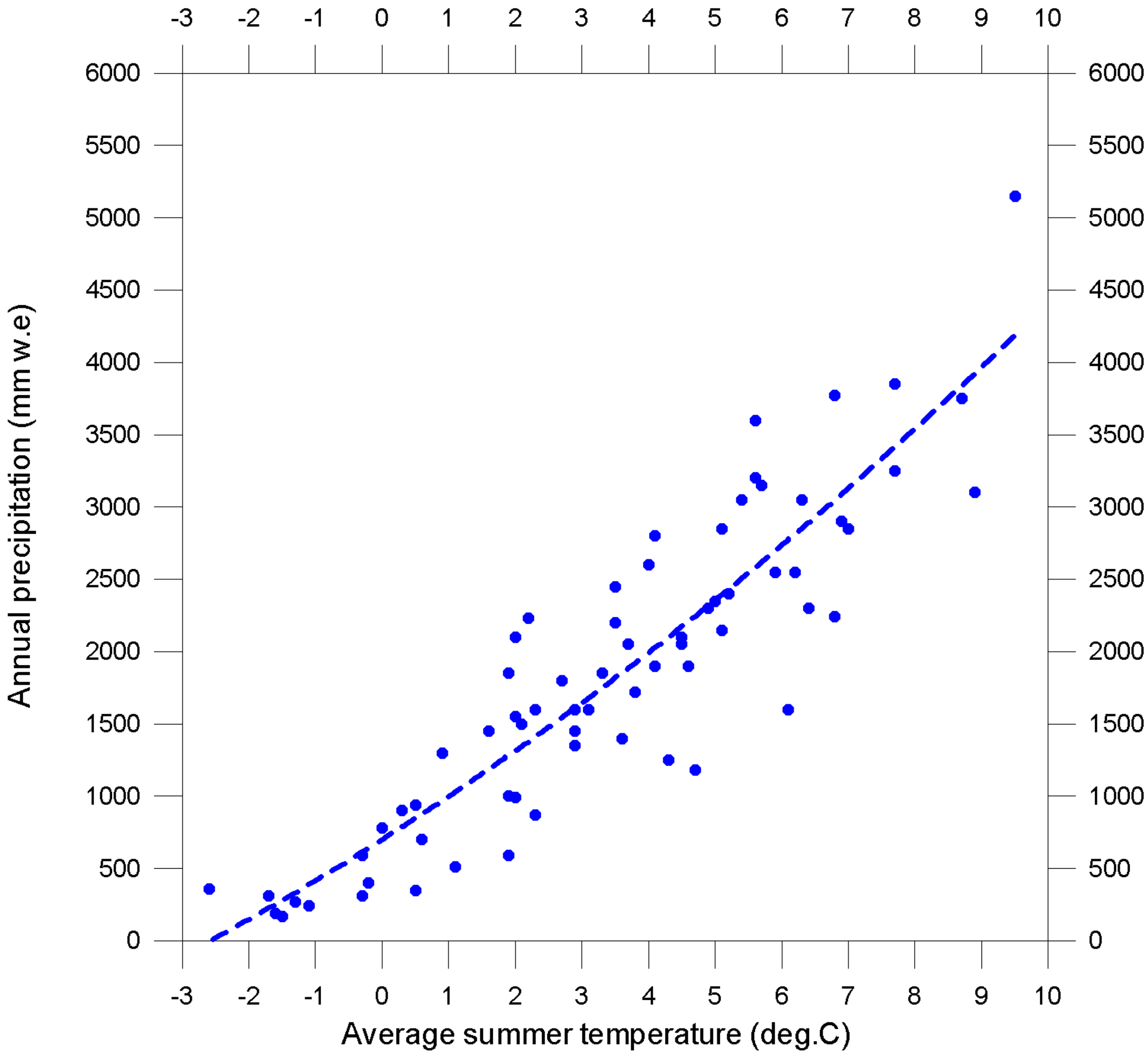
Glaciers


Mean annual air temperature (C)
-15
-10
-7
-6
-5
-2
0
3.5
5
mean equilibrium line on glaciers
NE Greenland (74N,21W)
ELA
Continuous permafrost
LYR (78N,15E)
Sonnblick, Austria (47N, 14E)
cold firn
Discontinuous permafrost
W Greenland (70N,53W)
W Svalbard (78N,14E)
temperate firn
ELA
Slættaratindur
Faroe Islands (62N,7W)
Ben Nevis
Scotland (57N,5W)
Zone of potential glaciation
SE Greenland (65N,37W)
Sporadic permafrost
Slettjøkull (64N,19W)
ELA
Periglacial, no permafrost
Kirkjubæjarklaustur (64N,18W)
Køtlujøkull (64N,19W)
Calm
Lower periglacial boundary
Lower periglacial boundary
Oslo (60N,11E)
Windy
Reykjavik (64N,22W)
Torshavn (62N,7W)
Vik (63N,19W)
Bergen (60N,5E)
Aberdeen (57N,2W)
Darjeeling (27N,88E)
500
1000
1500
2000
2500
3000
3500
Mean annual precipitation (mm w.e.)

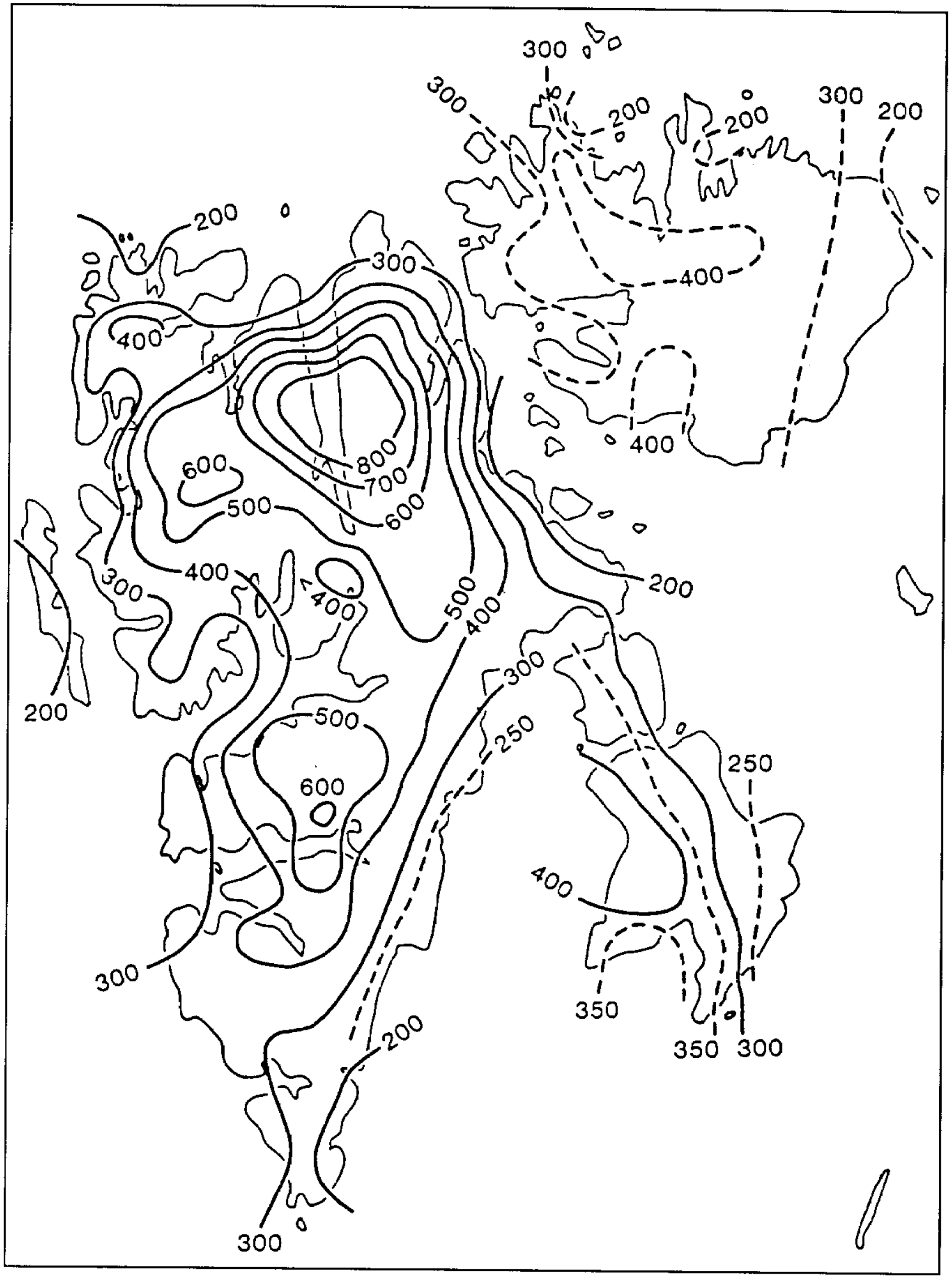
Ole Humlum

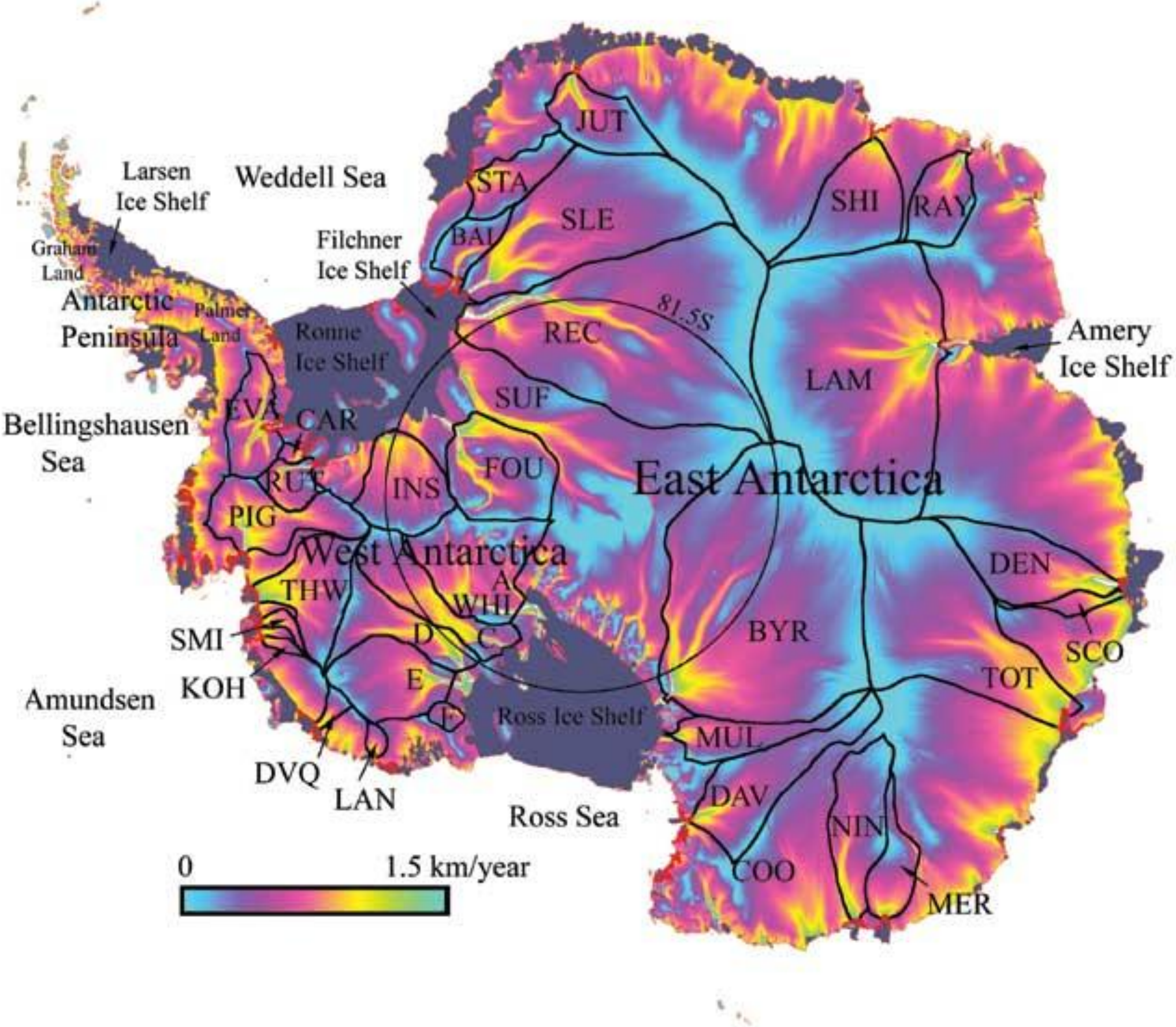
Equilibrium line altitude (ELA)



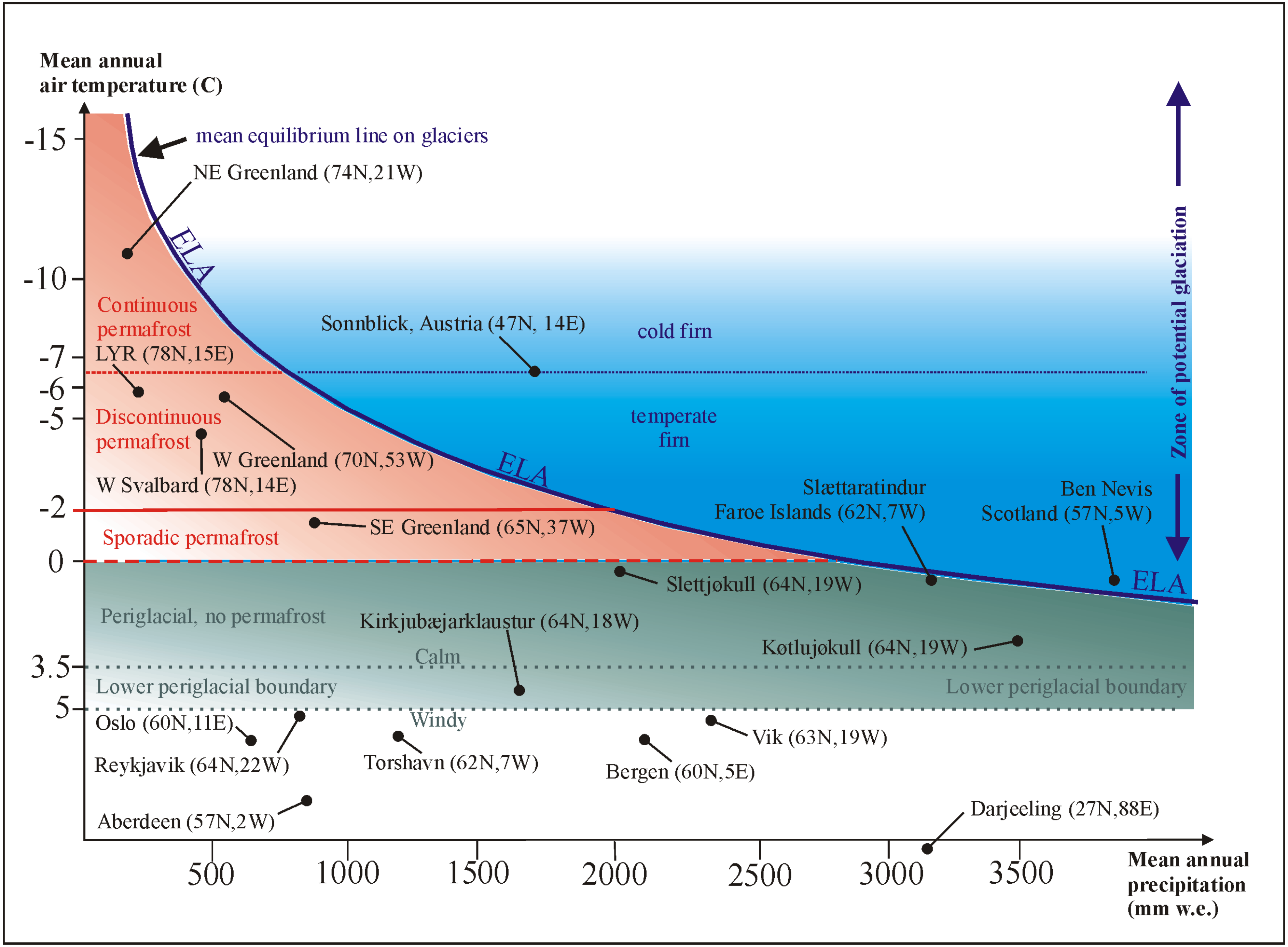


Annual precipitation (mm w.e)
Average summer temperature (deg.C)
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000


300
300
200
200
300
200
200
300
400
400
800
700
600
600
500
400
200
300
400
500
400
200
300
500
250
250
600
400
300
350
200
350
300
300


Larsen Ice Shelf
Weddell Sea
Graham Land
Antarctic Peninsula
Palmer Land
Filchner Ice Shelf
Ronne Ice Shelf
Bellingshausen Sea
Amundsen Sea
Ross Sea
Ross Ice Shelf
Amery Ice Shelf
East Antarctica
West Antarctica
81.5S
JUT
STA
SLE
BAL
SHI
RAY
REC
LAM
SUF
FOU
INS
EVA
CAR
RUT
PIG
THW
A
WHI
C
D
E
F
SMI
KOH
DVQ
LAN
BYR
DEN
SCO
TOT
MUL
DAV
COO
NIN
MER
0
1.5 km/year

The periglacial environment


Mean annual
air temperature (C)
-15
-10
-7
-6
-5
-2
0
3.5
5
mean equilibrium line on glaciers
NE Greenland (74N,21W)
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Continuous
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cold firn
Discontinuous
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W Greenland (70N,53W)
W Svalbard (78N,14E)
temperate
firn
ELA
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Calm
Lower periglacial boundary
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Oslo (60N,11E)
Windy
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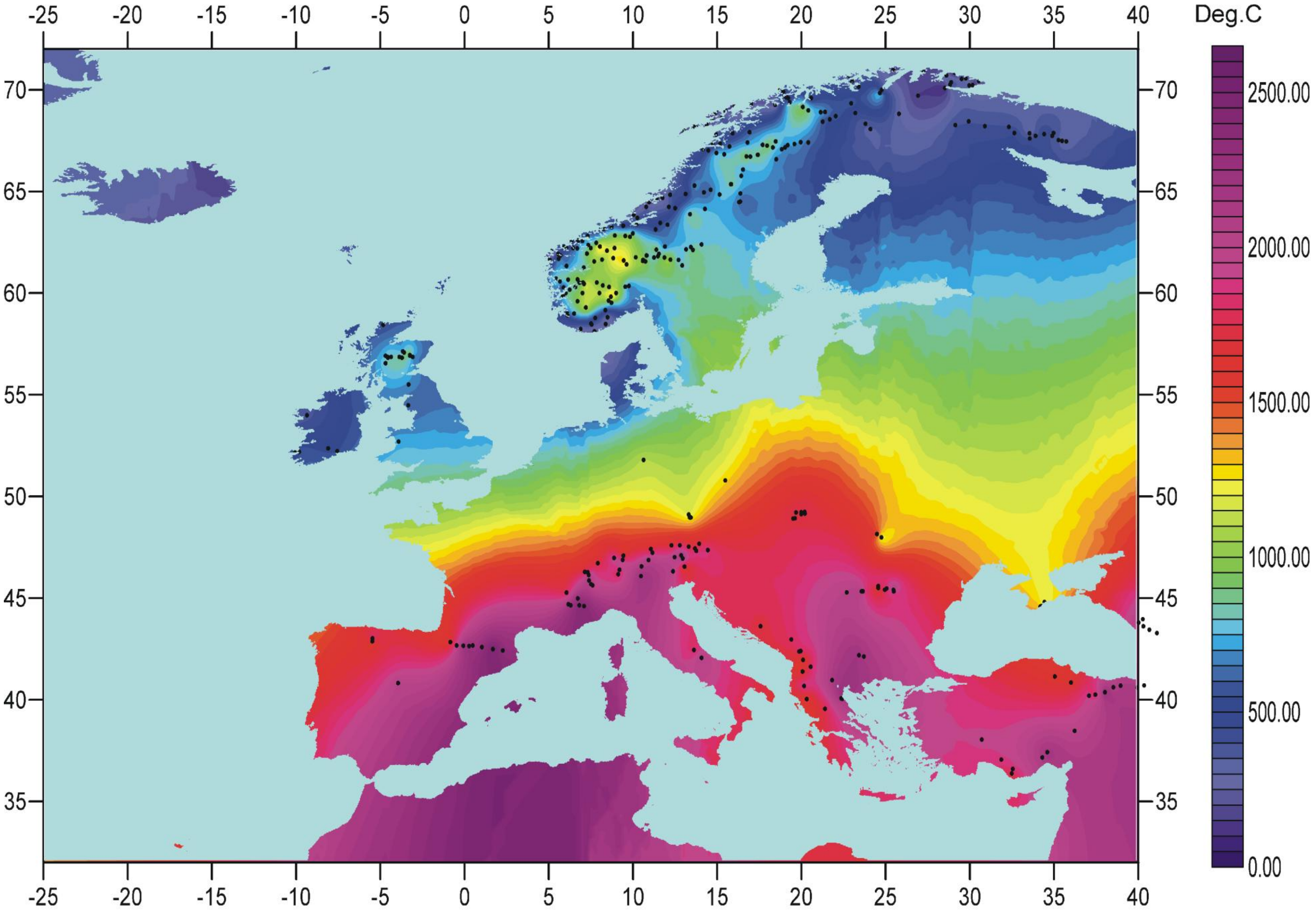
Torshavn (62N,7W)
Vik (63N,19W)
Bergen (60N,5E)
Aberdeen (57N,2W)
Darjeeling (27N,88E)
500
1000
1500
2000
2500
3000
3500
Mean annual
precipitation
(mm w.e.)

Ole Humlum

The tree line

Trees bend by soil creep and snow pressure

Tree Line Europe From Satellites 2006



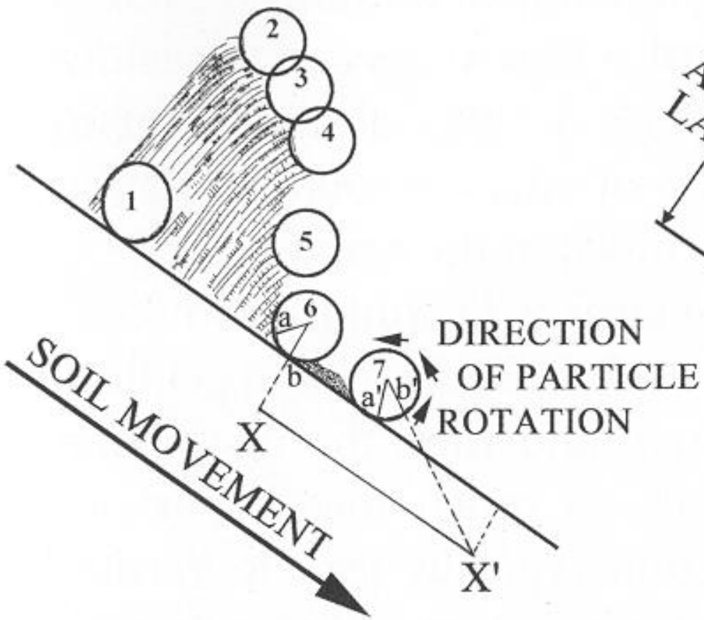
Periglacial environments

Thre main types
of periglacial environments

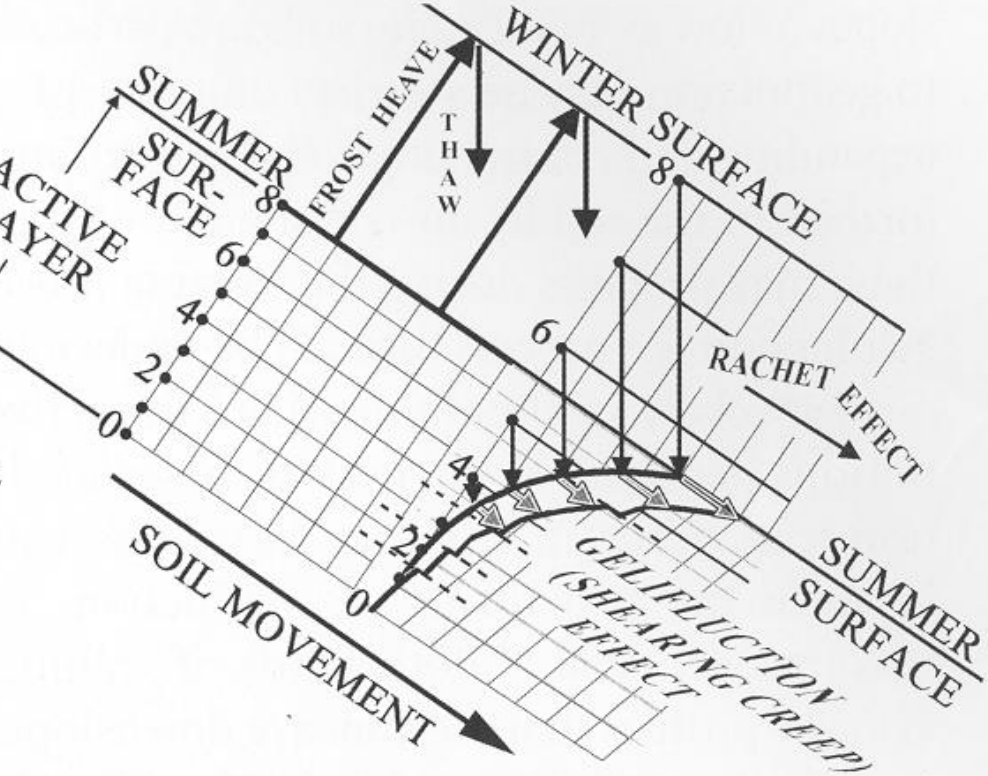
Periglacial processes

Needle ice


CANADA
2 DOLLARS



PIPKRAKE
(NEEDLE ICE)
SOIL TRANSPORT

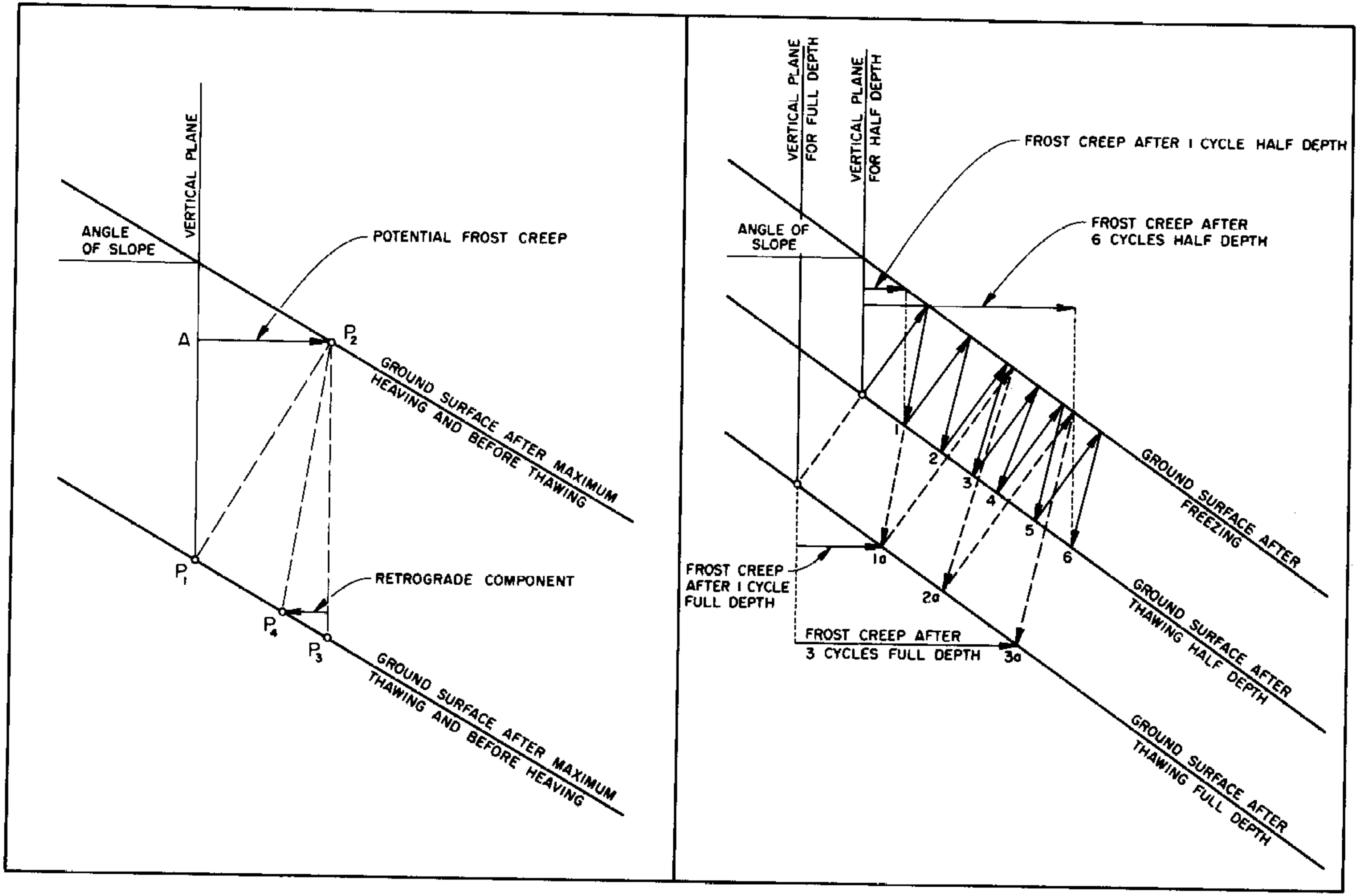


FROST CREEP (FROST HEAVE RATCHETING)
AND GELEFRACTION (SHEARING) CREEP

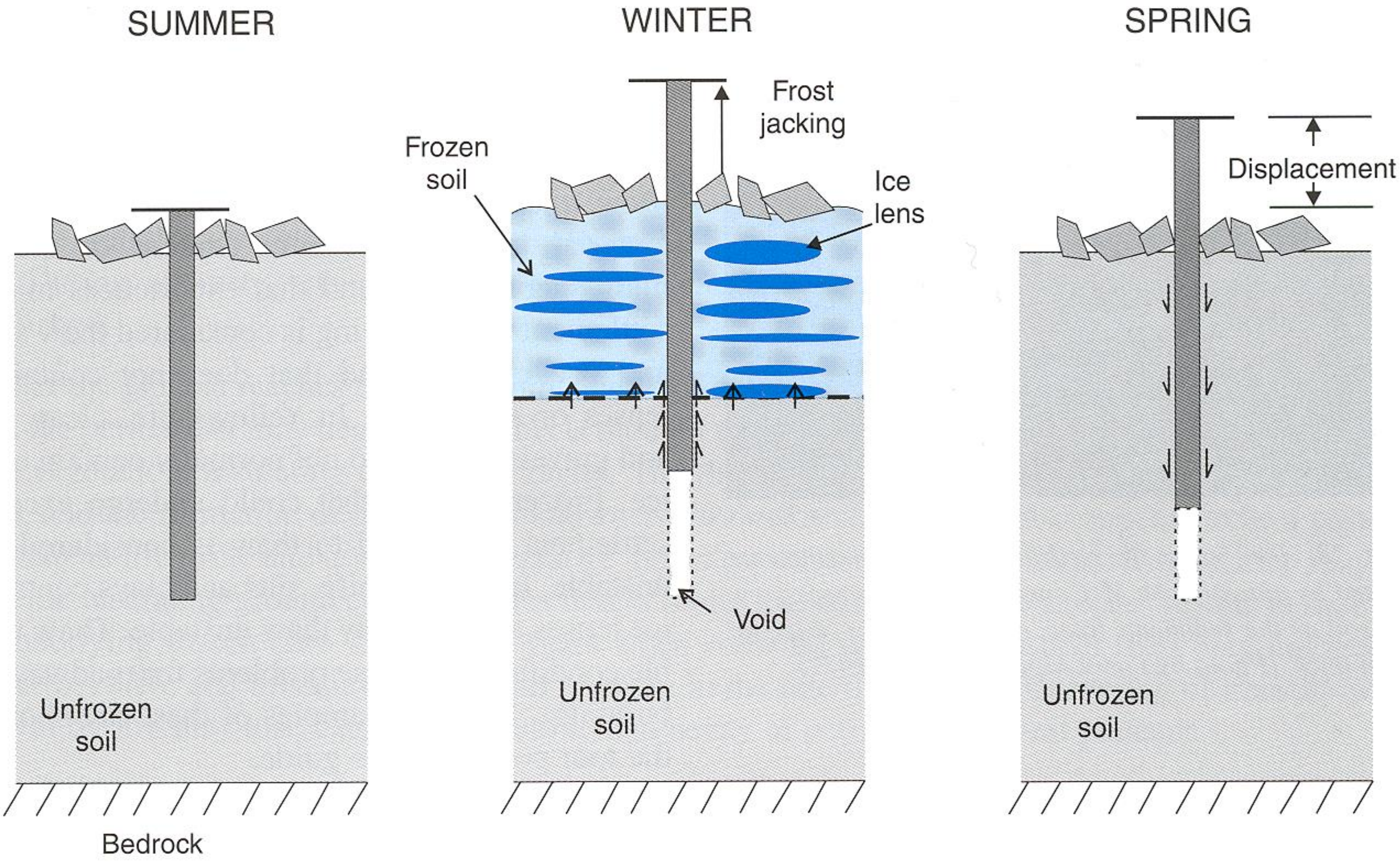
Needle ice, Oslo

Needle ice, Dalton Highway, Alaska

Surface lift by needle ice, Småland, Sweden


VERTICAL PLANE
ANGLE OF SLOPE
POTENTIAL FROST CREEP
A
P_2
GROUND SURFACE AFTER MAXIMUM HEAVING AND BEFORE THAWING
P_1
RETROGRADE COMPONENT
P_4
P_3
GROUND SURFACE AFTER MAXIMUM THAWING AND BEFORE HEAVING
VERTICAL PLANE FOR FULL DEPTH
VERTICAL PLANE FOR HALF DEPTH
FROST CREEP AFTER 1 CYCLE HALF DEPTH
ANGLE OF SLOPE
FROST CREEP AFTER 6 CYCLES HALF DEPTH
1
2
3
4
5
6
GROUND SURFACE AFTER FREEZING
FROST CREEP AFTER 1 CYCLE FULL DEPTH
1a
2a
3a
FROST CREEP AFTER 3 CYCLES FULL DEPTH
GROUND SURFACE AFTER THAWING HALF DEPTH
GROUND SURFACE AFTER THAWING FULL DEPTH

Frost heave


SUMMER
WINTER
SPRING
Frost jacking
Frozen soil
Ice lens
Displacement
Void
Unfrozen soil
Unfrozen soil
Unfrozen soil
Bedrock

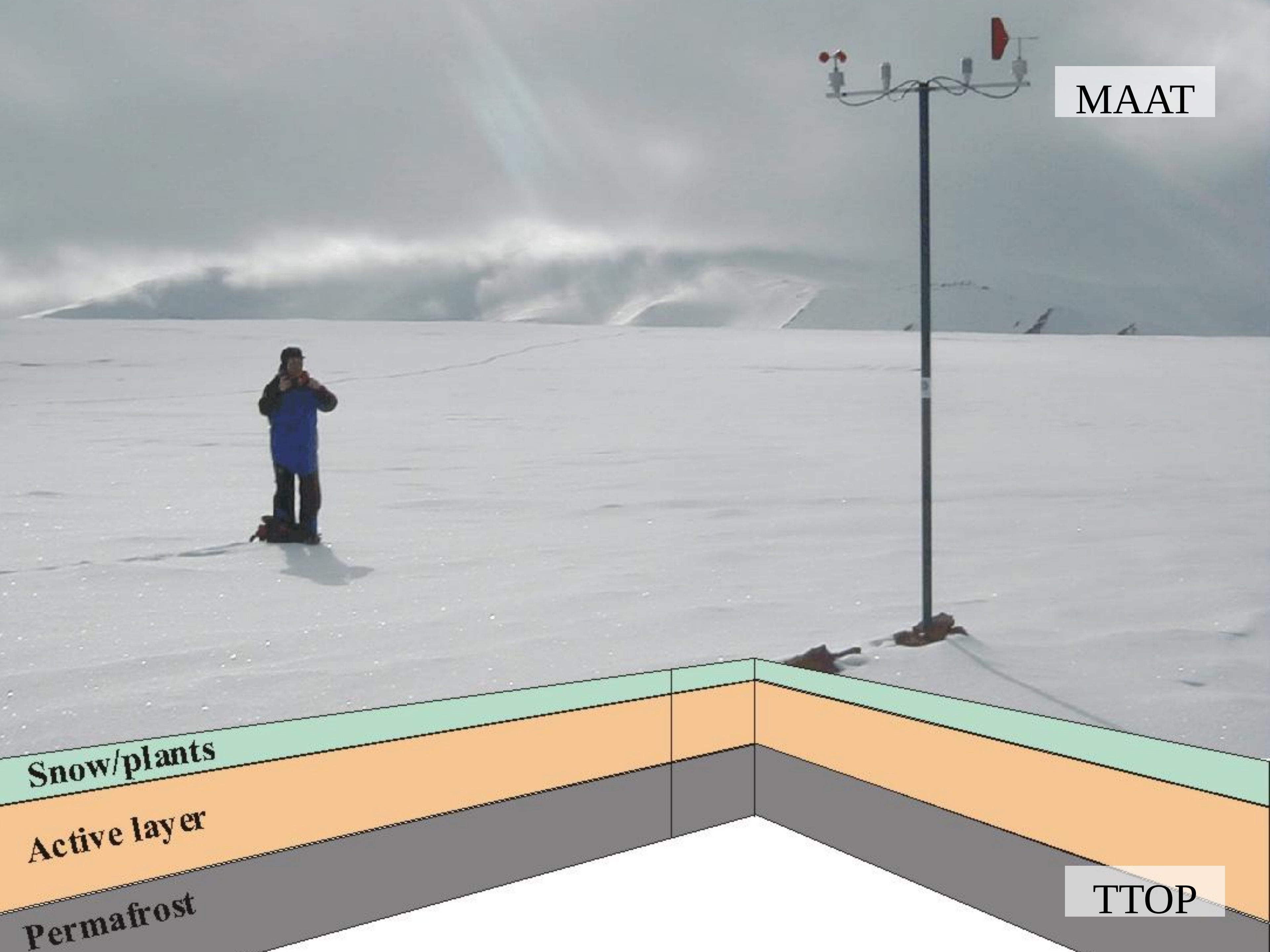
Snow
and wind transport of snow

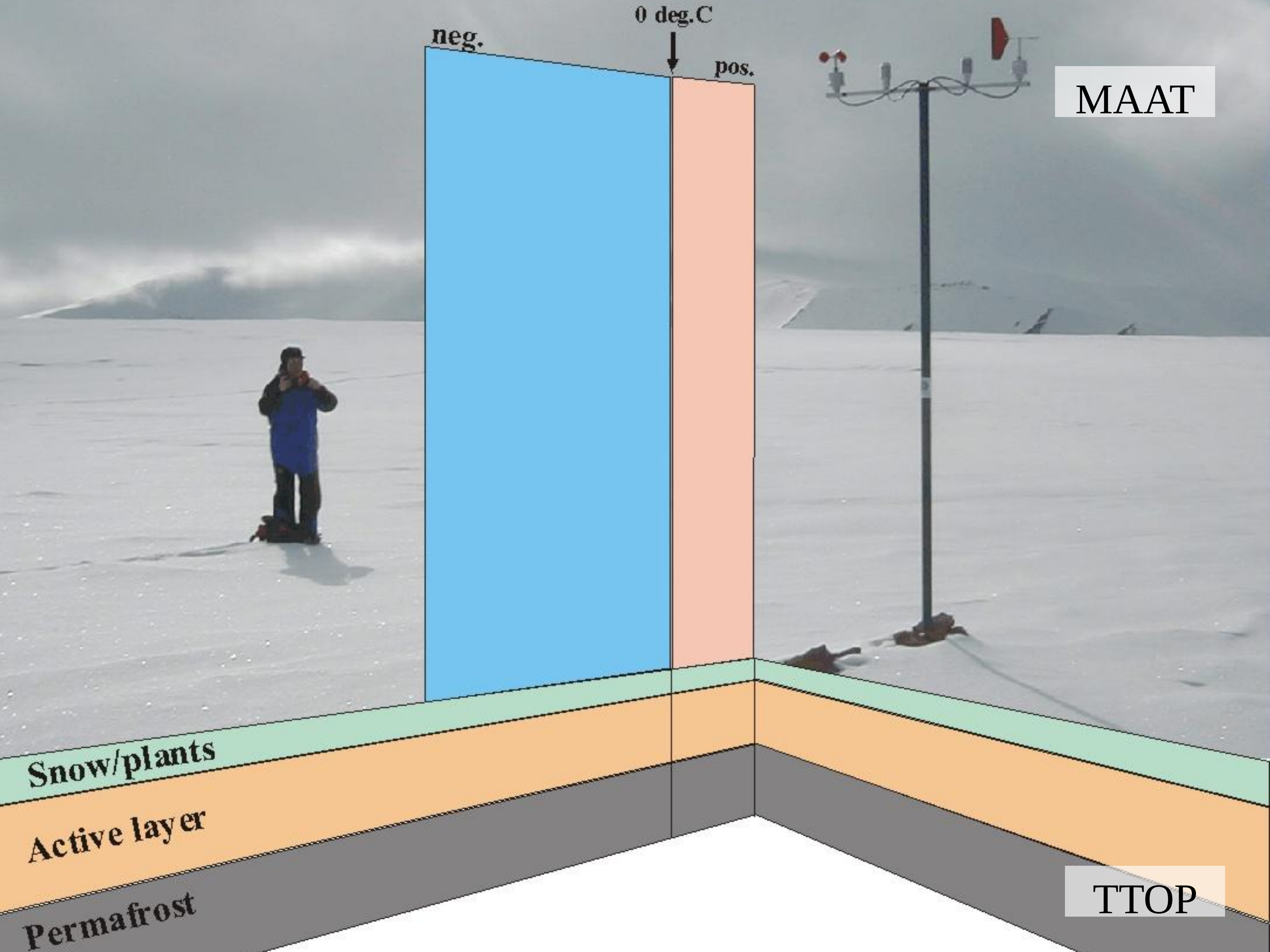
Trees bend by soil creep and snow pressure

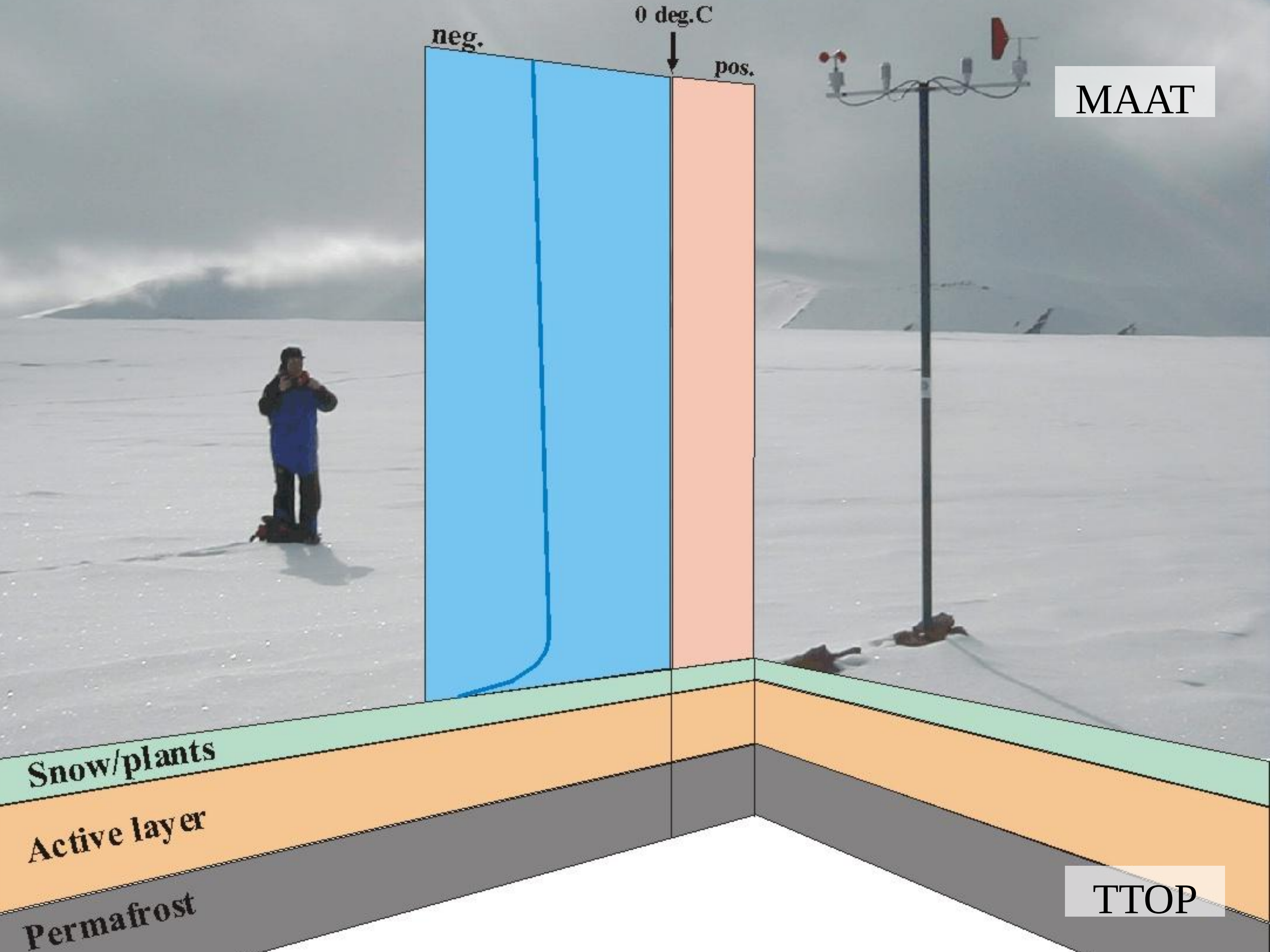
Snow and ground temperature

MAAT

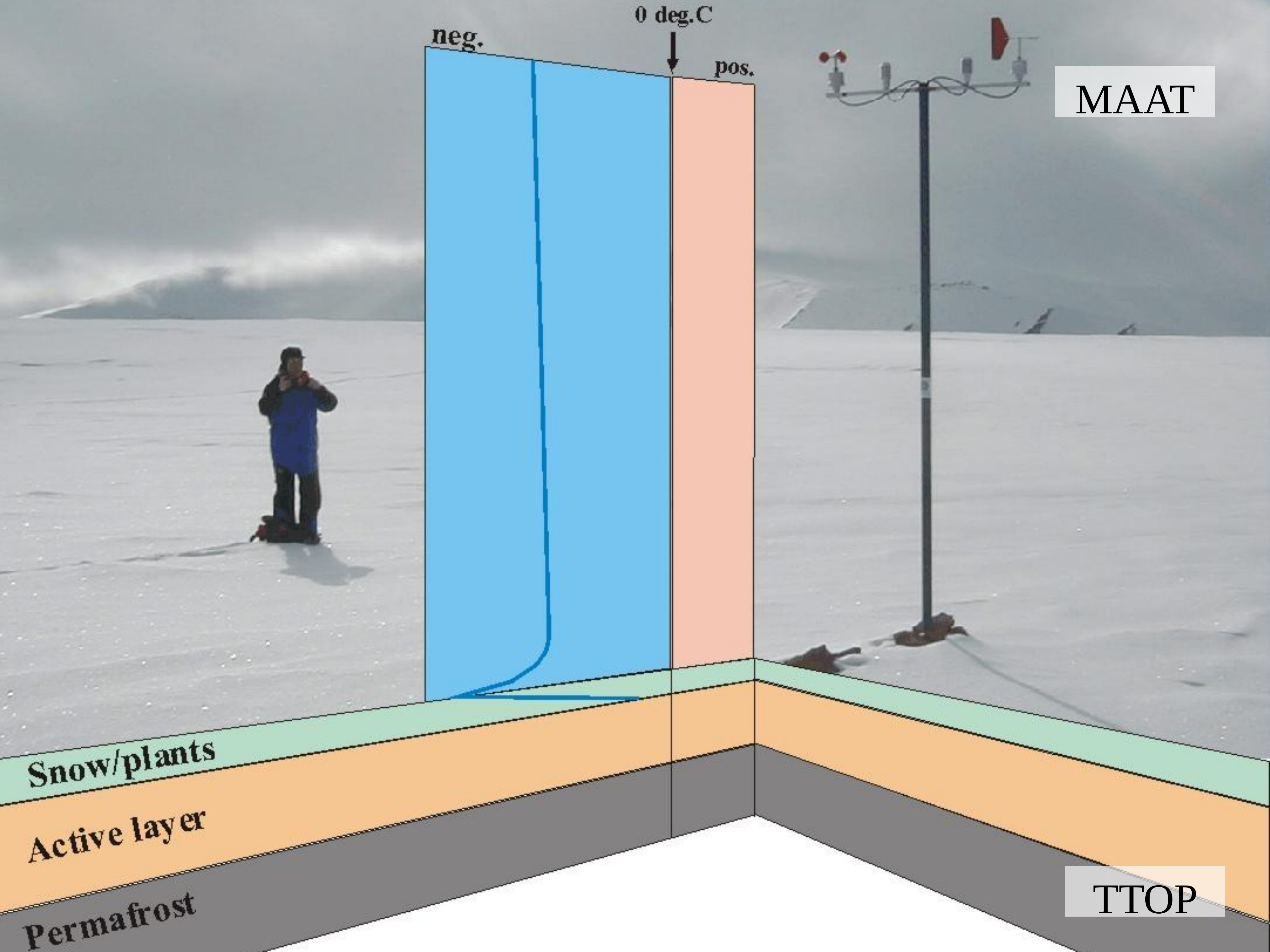
Gruvefjellet meteorological station, central Spitsbergen, Svalbard, 18th May 2002

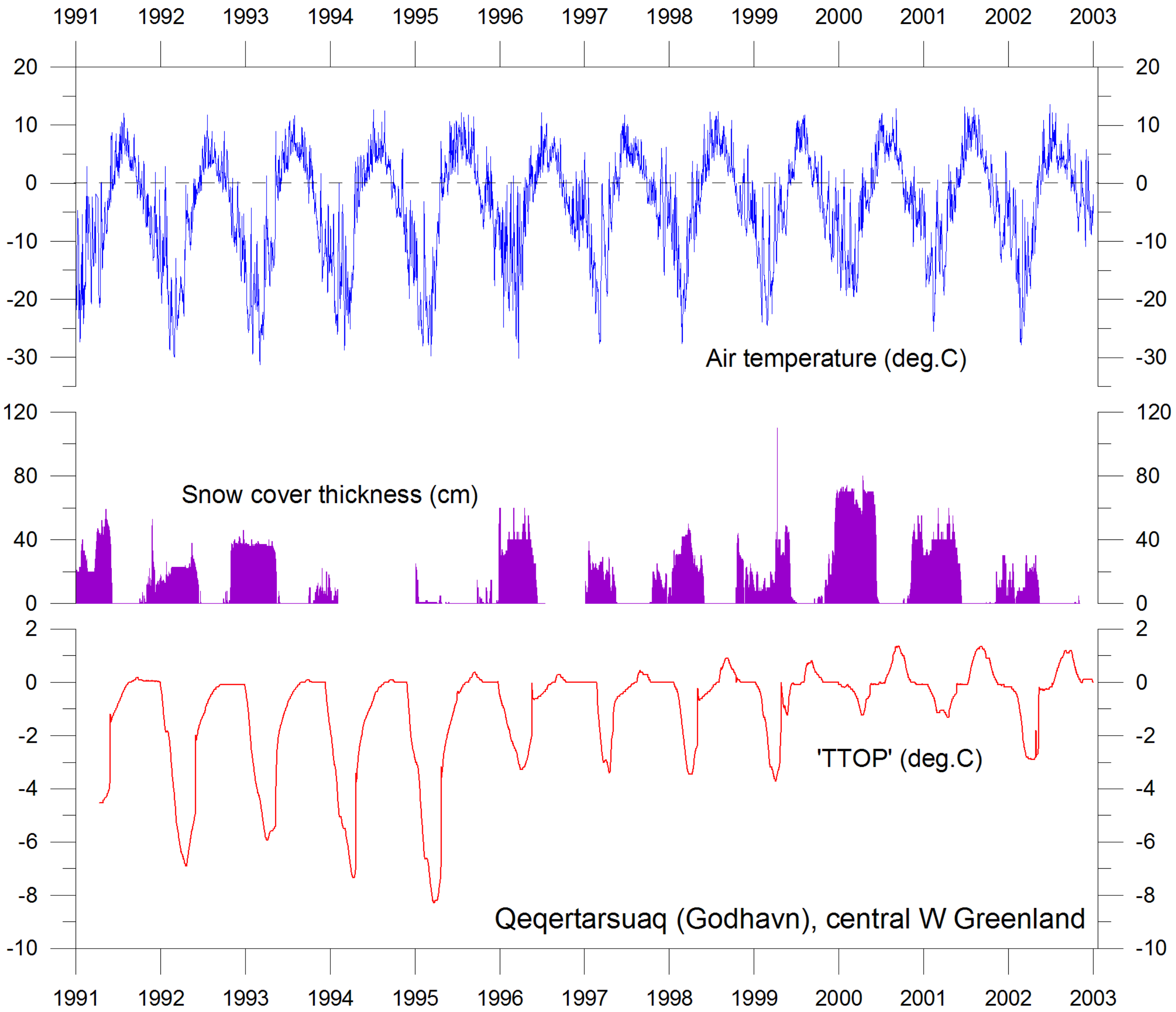

MAAT
Snow/plants
Active layer
Permafrost
TTOP


0 deg.C
neg.
pos.
MAAT
Snow/plants
Active layer
Permafrost
TTOP



0 deg.C
neg.
pos.
MAAT
Snow/plants
Active layer
Permafrost
TTOP

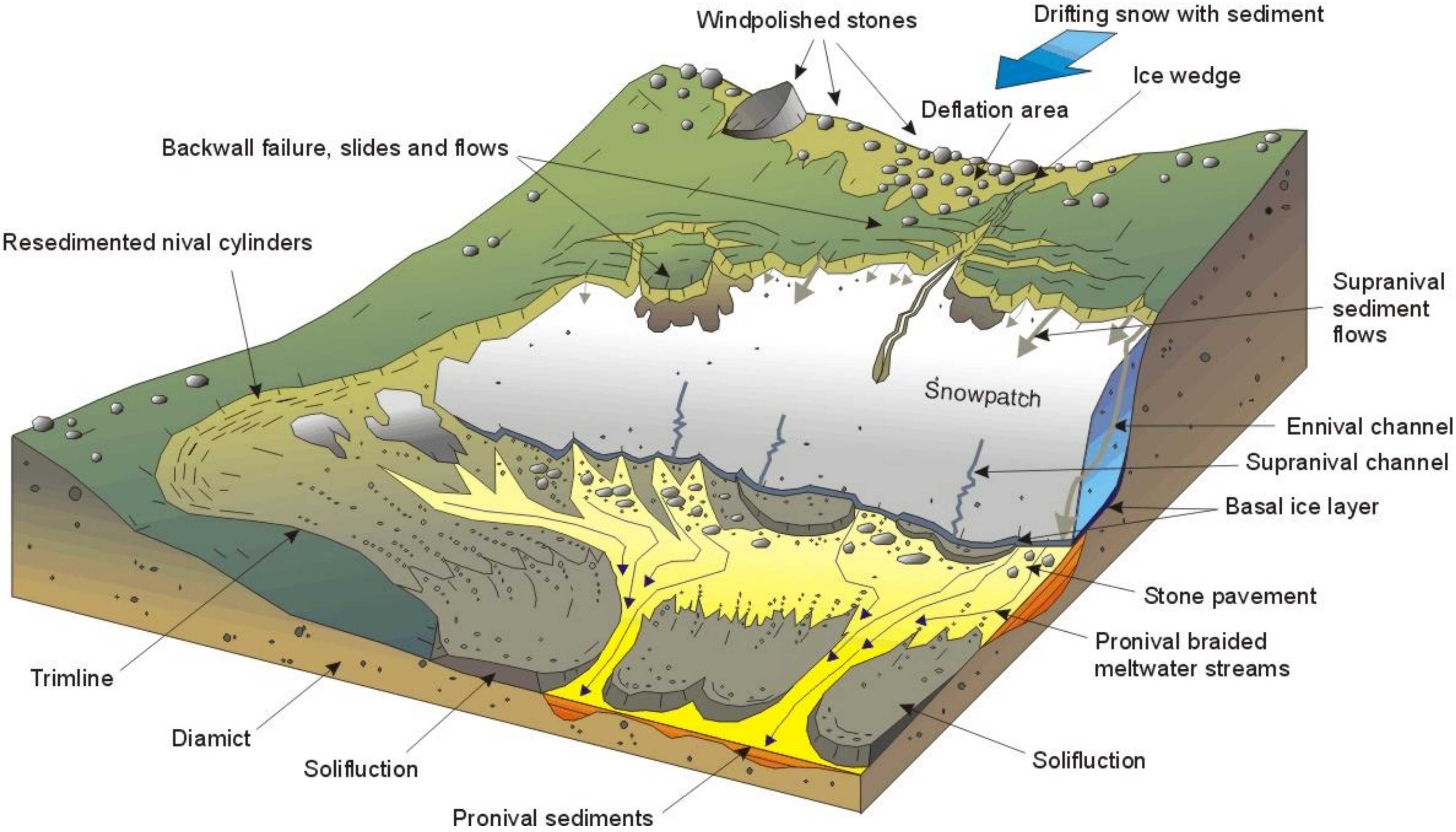

0 deg.C
neg.
pos.
MAAT
Snow/plants
Active layer
Permafrost
TTOP


1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
20
10
0
-10
-20
-30
Air temperature (deg.C)
120
80
40
0
Snow cover thickness (cm)
2
0
-2
-4
-6
-8
-10
'TTOP' (deg.C)
Qeqertarsuaq (Godhavn), central W Greenland

Nivation:
The geomorphological effect of snow

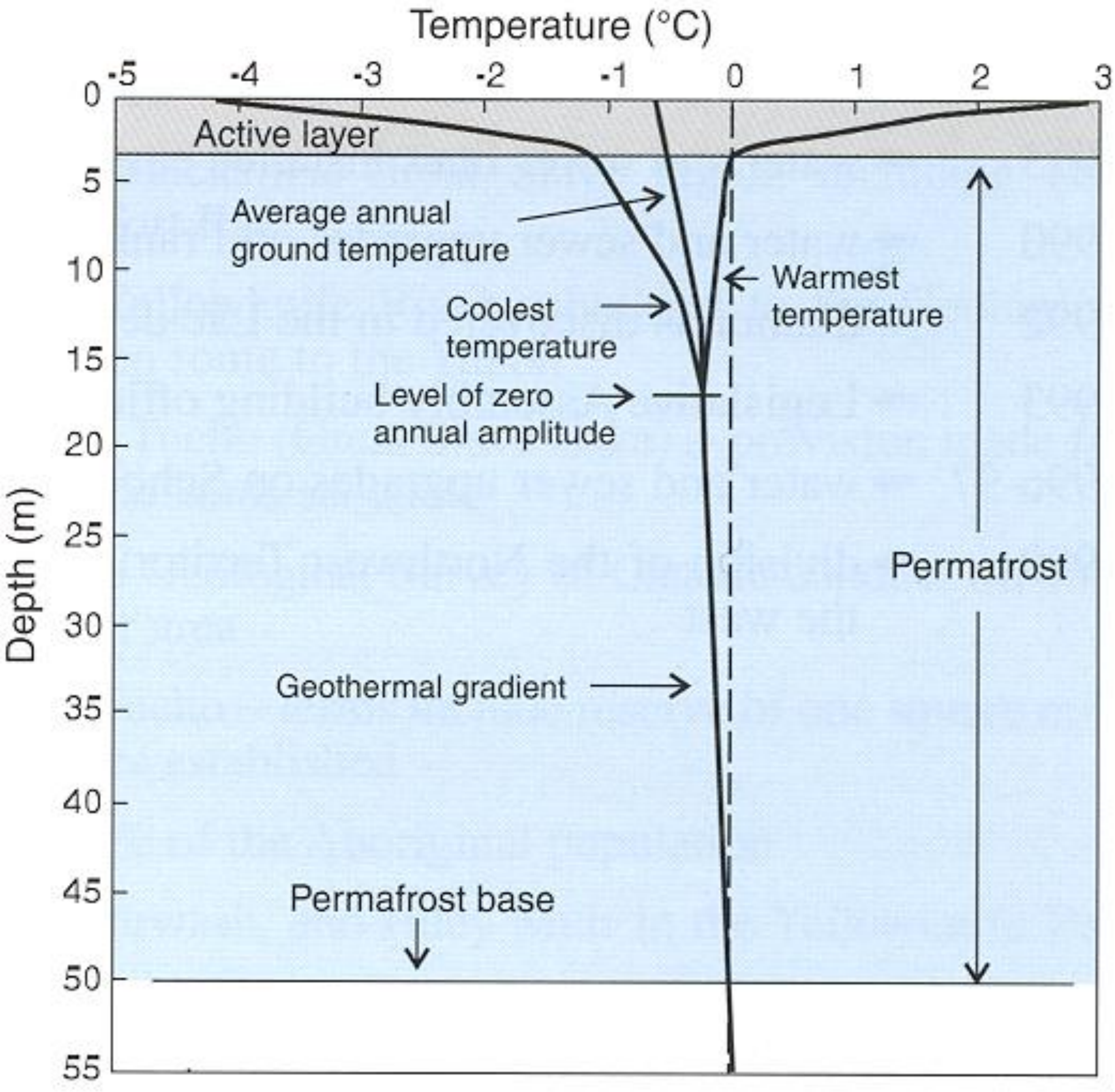
Nivation hollows

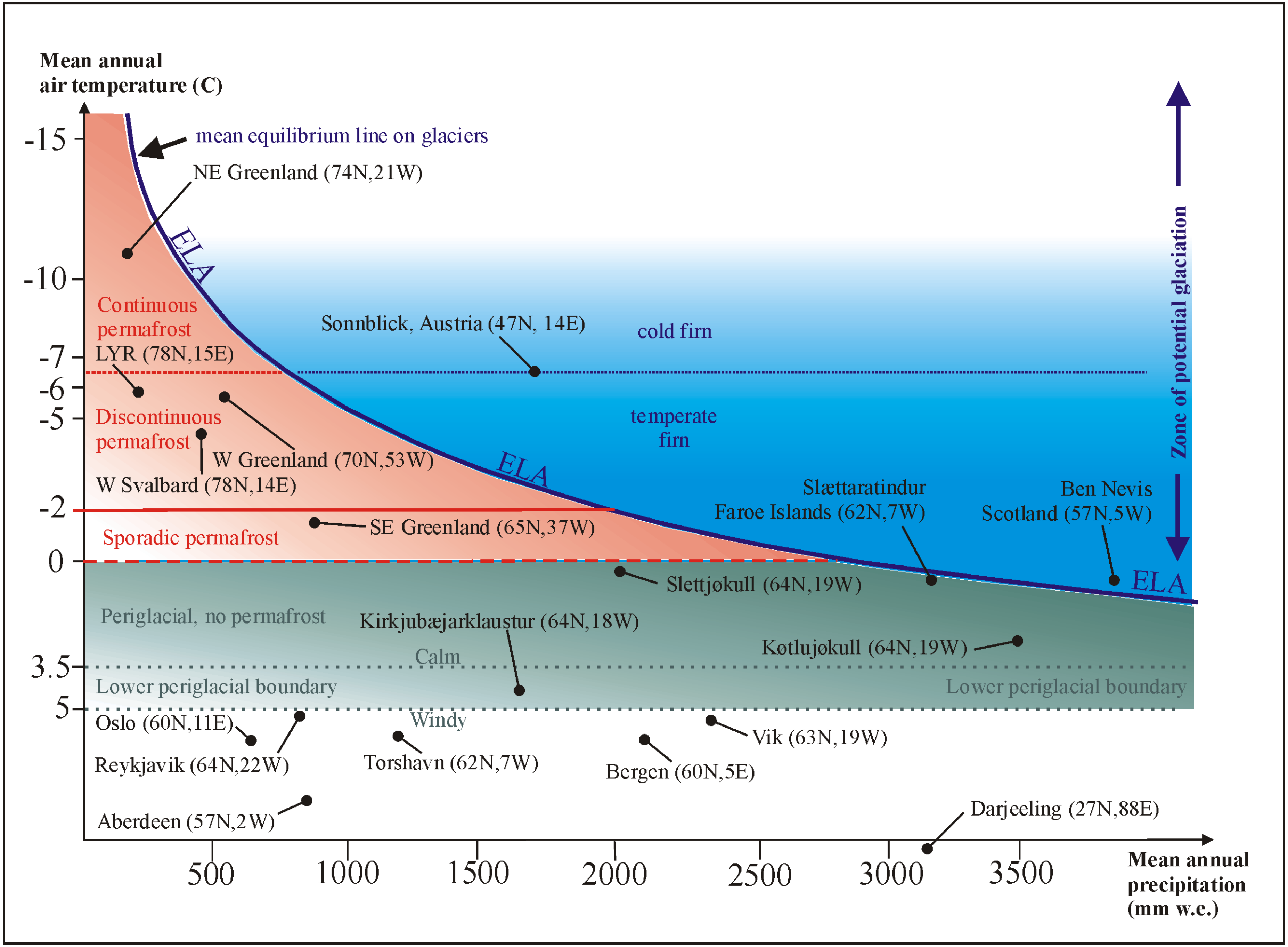
High Arctic Nivation Process-Form-Sediment Model



Permafrost

Thickness of permafrost ?

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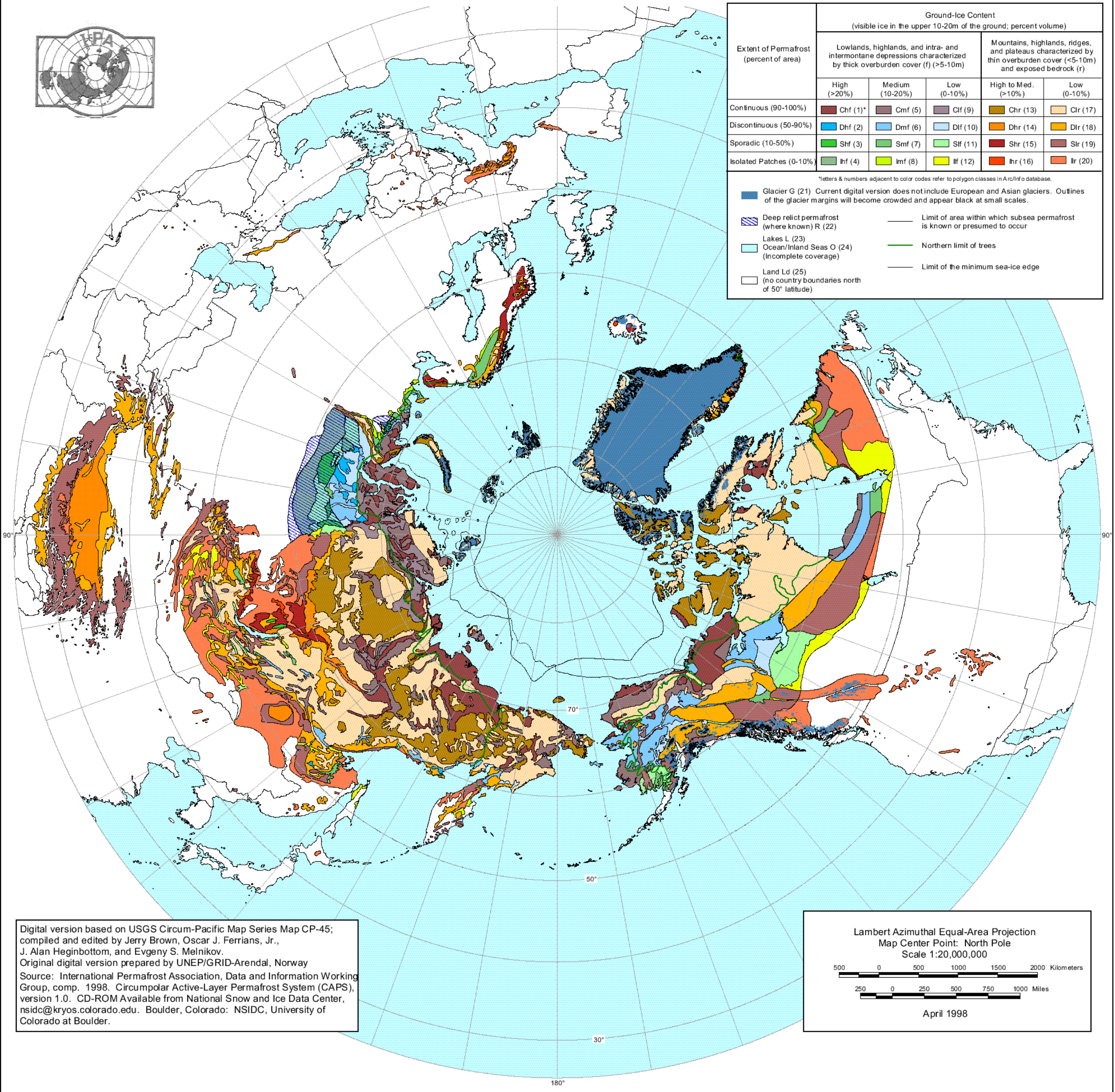
Calm
Lower periglacial boundary
Lower periglacial boundary
Oslo (60N,11E)
Windy
Reykjavik (64N,22W)
Torshavn (62N,7W)
Vik (63N,19W)
Bergen (60N,5E)
Aberdeen (57N,2W)
Darjeeling (27N,88E)
500
1000
1500
2000
2500
3000
3500
Mean annual
precipitation
(mm w.e.)

Ole Humlum

CIRCUM-ARCTIC MAP OF PERMAFROST AND GROUND-ICE CONDITIONS



Extent of Permafrost (percent of area)	Ground-Ice Content (visible ice in the upper 10-20m of the ground; percent volume)				
	Lowlands, highlands, and intra- and intermontane depressions characterized by thick overburden cover (f) (>5-10m)			Mountains, highlands, ridges, and plateaus characterized by thin overburden cover (<5-10m) and exposed bedrock (r)	
	High (>20%)	Medium (10-20%)	Low (0-10%)	High to Med. (>10%)	Low (0-10%)
Continuous (90-100%)	■ Chf (1)*	■ Cmf (5)	■ Clf (9)	■ Chr (13)	■ Clr (17)
Discontinuous (50-90%)	■ Dhf (2)	■ Dmf (6)	■ Dlf (10)	■ Dhr (14)	■ Dlr (18)
Sporadic (10-50%)	■ Shf (3)	■ Smf (7)	■ Slf (11)	■ Shr (15)	■ Slr (19)
Isolated Patches (0-10%)	■ Ihf (4)	■ Imf (8)	■ Ilf (12)	■ Ihr (16)	■ Ilr (20)

*letters & numbers adjacent to color codes refer to polygon classes in Arc/Info database.

■ Glacier G (21) Current digital version does not include European and Asian glaciers. Outlines of the glacier margins will become crowded and appear black at small scales.

▨ Deep relict permafrost (where known) R (22)

□ Lakes L (23)
Ocean/Inland Seas O (24)
(Incomplete coverage)

□ Land Ld (25)
(no country boundaries north of 50° latitude)

— Limit of area within which subsea permafrost is known or presumed to occur

— Northern limit of trees

— Limit of the minimum sea-ice edge

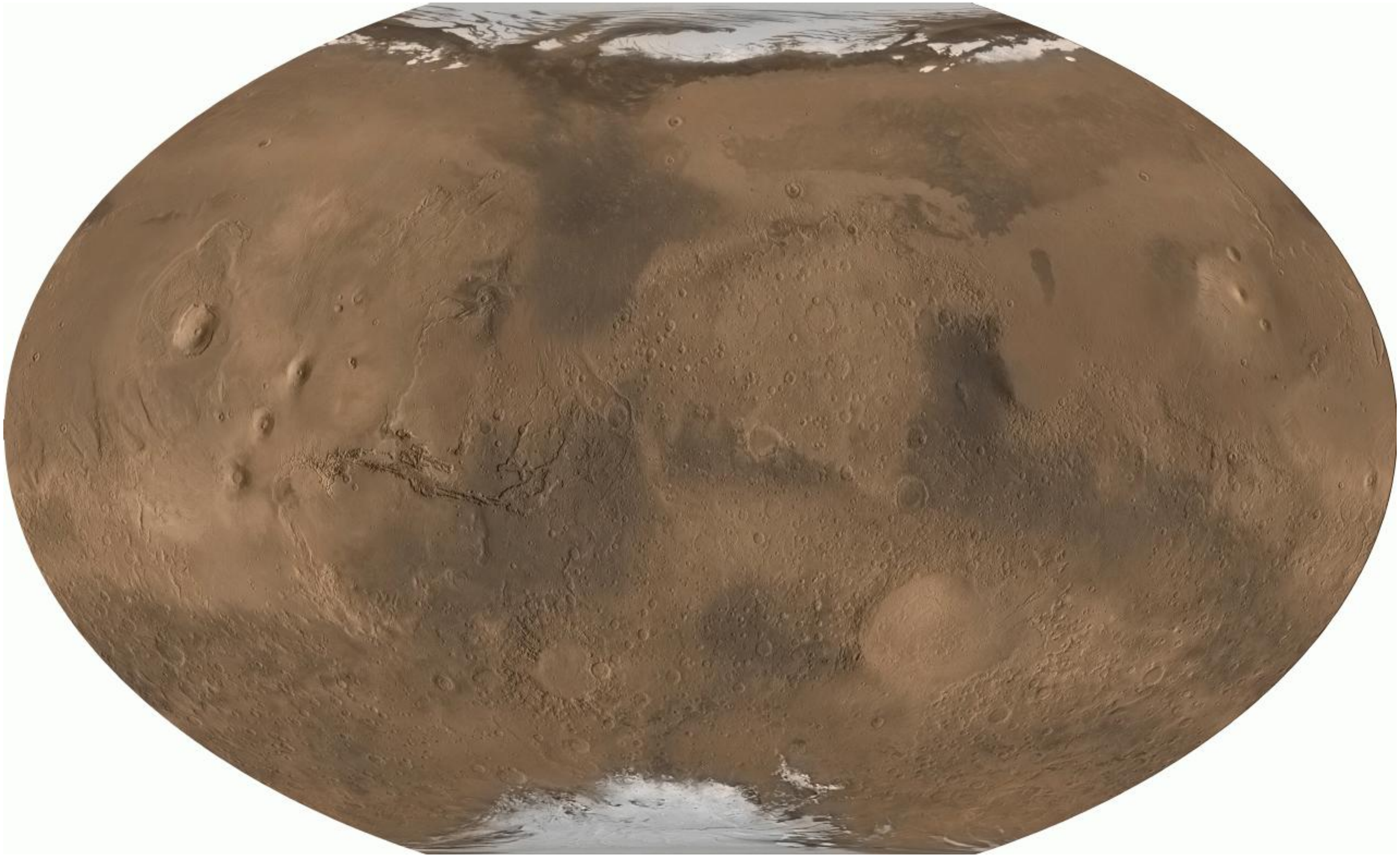
Digital version based on USGS Circum-Pacific Map Series Map CP-45; compiled and edited by Jerry Brown, Oscar J. Ferrians, Jr., J. Alan Heginbottom, and Evgeny S. Melnikov.
Original digital version prepared by UNEP/GRID-Arendal, Norway
Source: International Permafrost Association, Data and Information Working Group, comp. 1998. Circumpolar Active-Layer Permafrost System (CAPS), version 1.0. CD-ROM Available from National Snow and Ice Data Center, nsidc@kryos.colorado.edu. Boulder, Colorado: NSIDC, University of Colorado at Boulder.

Lambert Azimuthal Equal-Area Projection
Map Center Point: North Pole
Scale 1:20,000,000

500 0 500 1000 1500 2000 Kilometers

250 0 250 500 750 1000 Miles

April 1998



Permafrost on other planets !