Alpine permafrost: A Victim of Climate Change?

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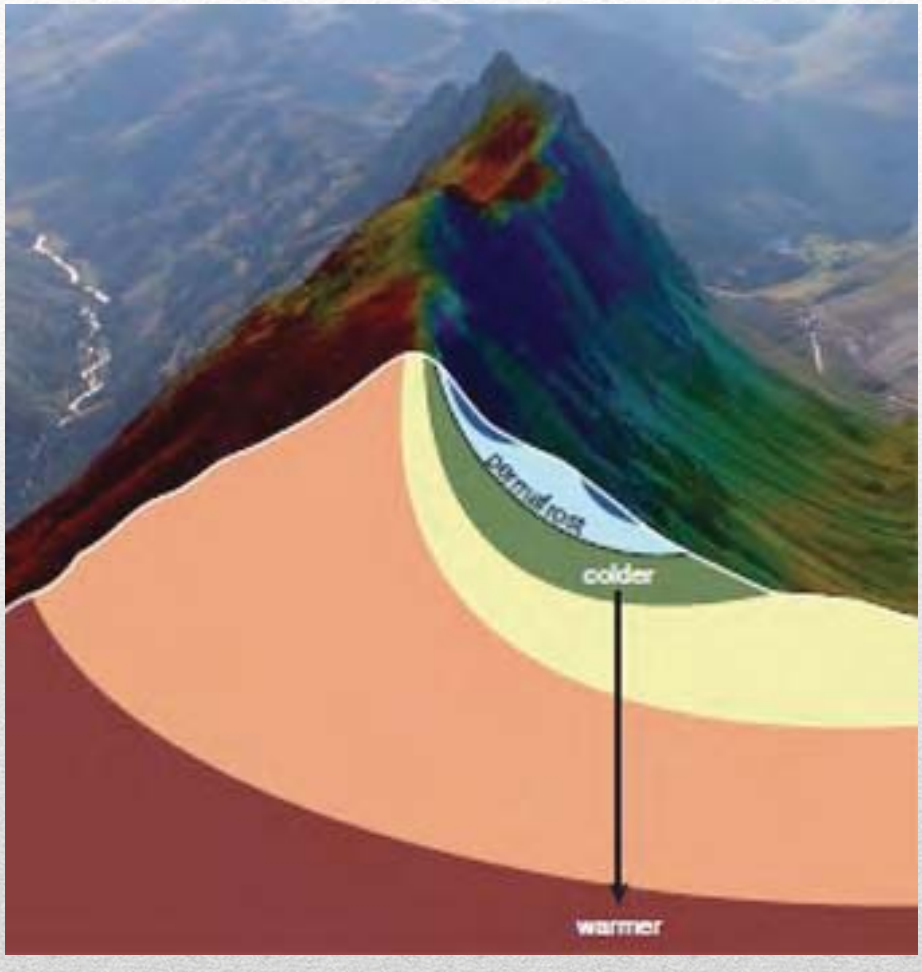
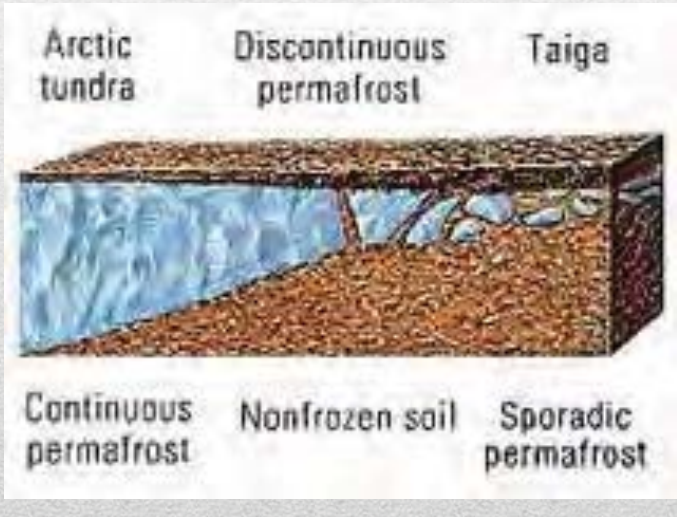
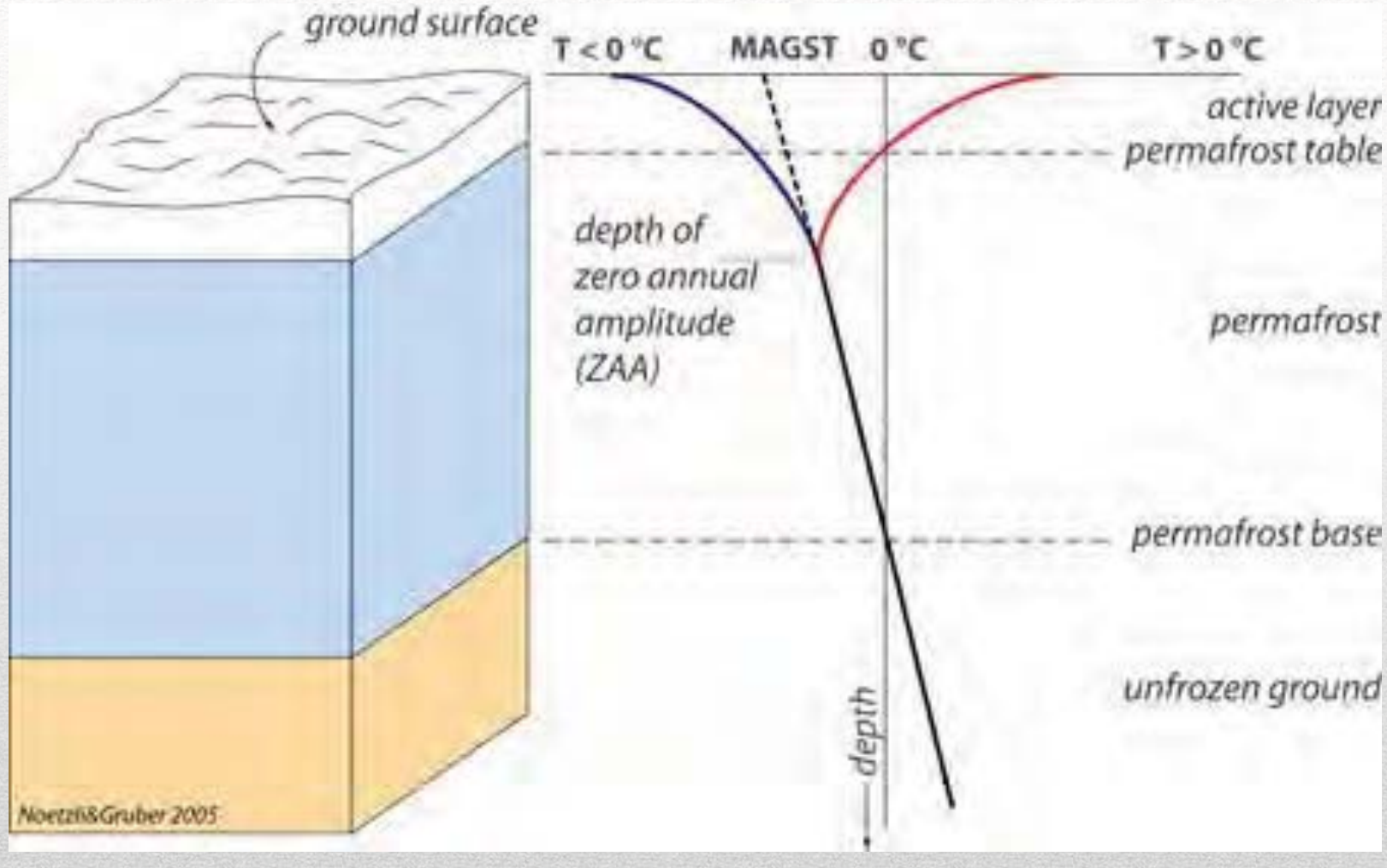
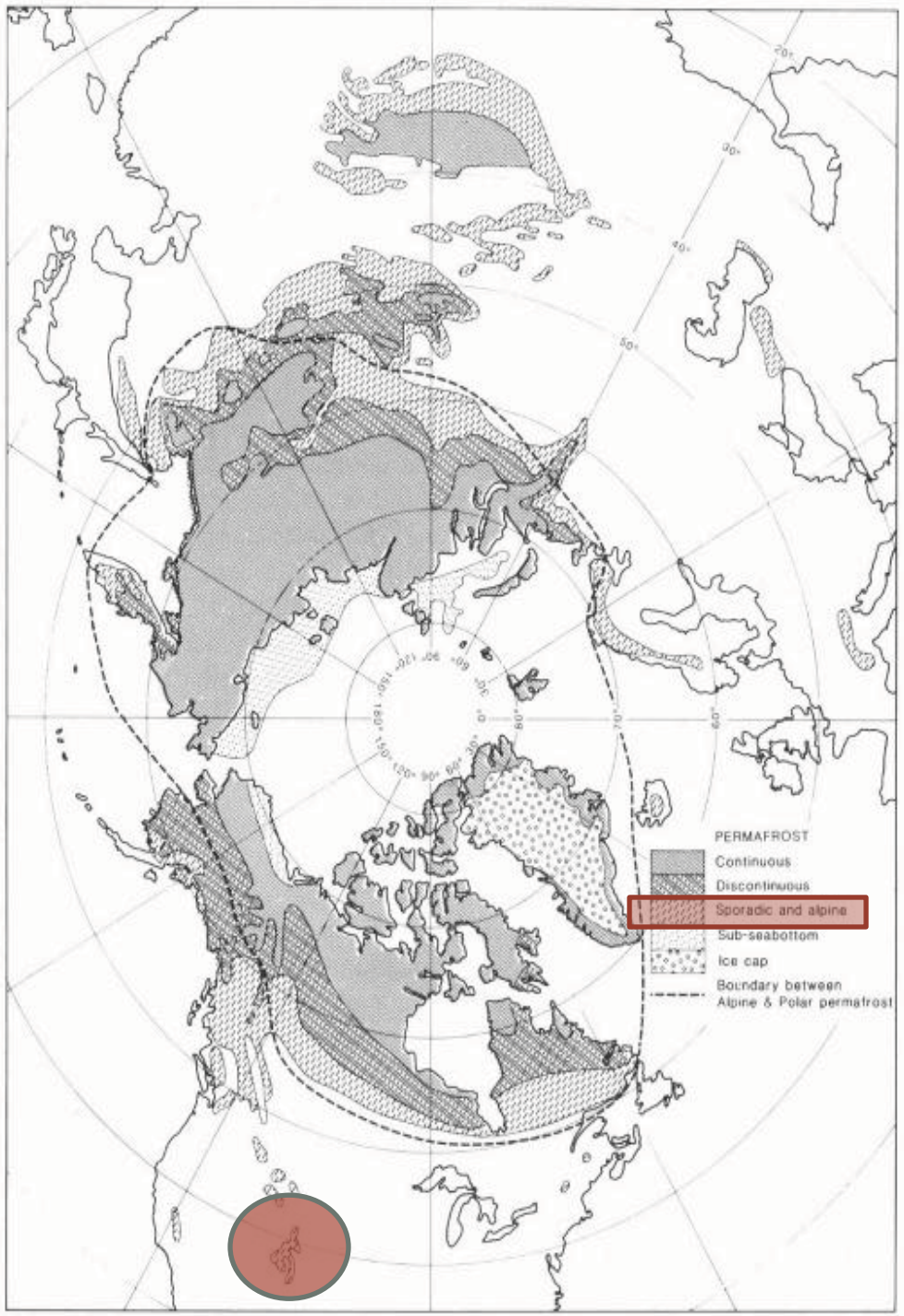




What is Permafrost?



Vertical Structure



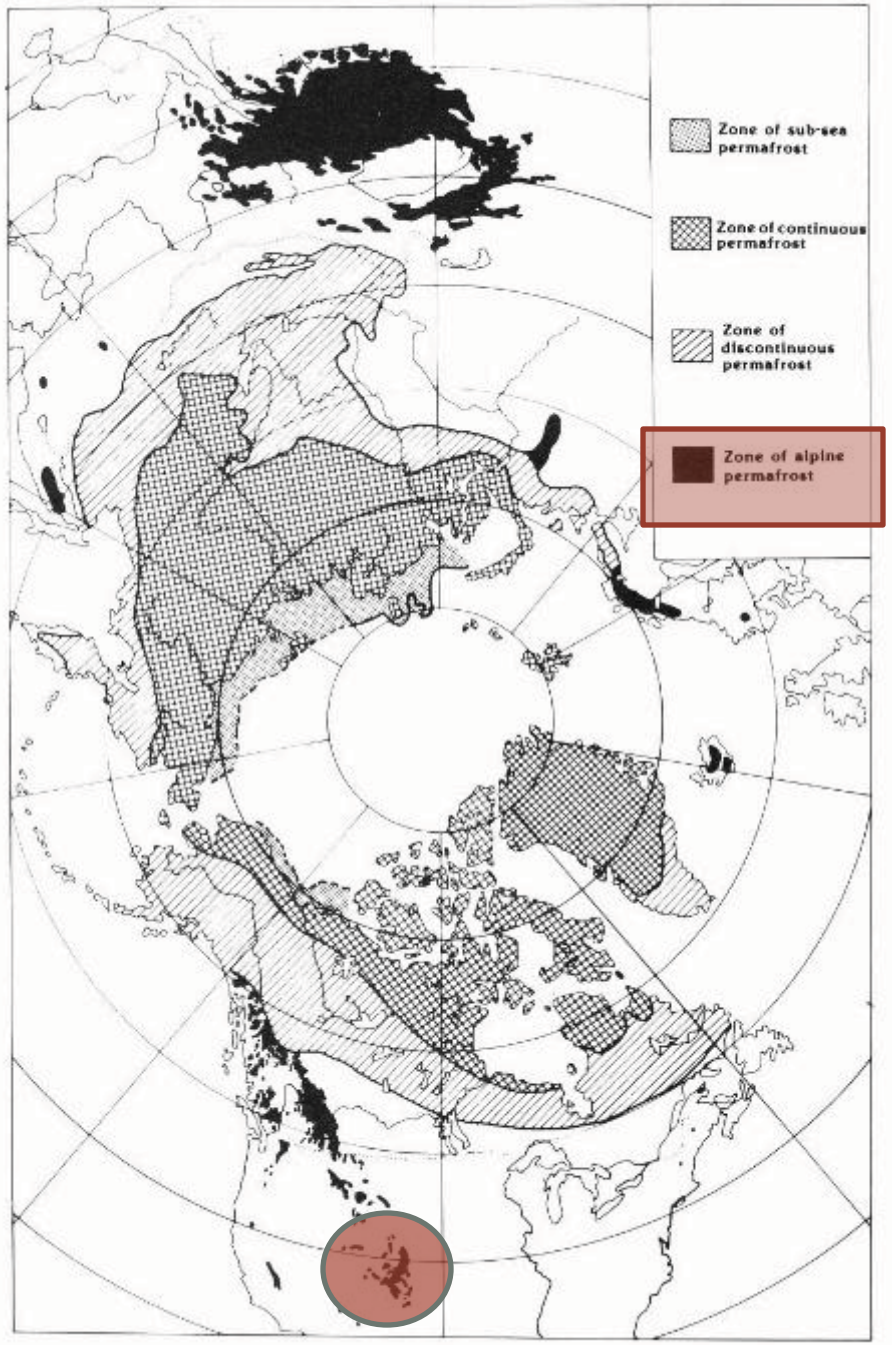
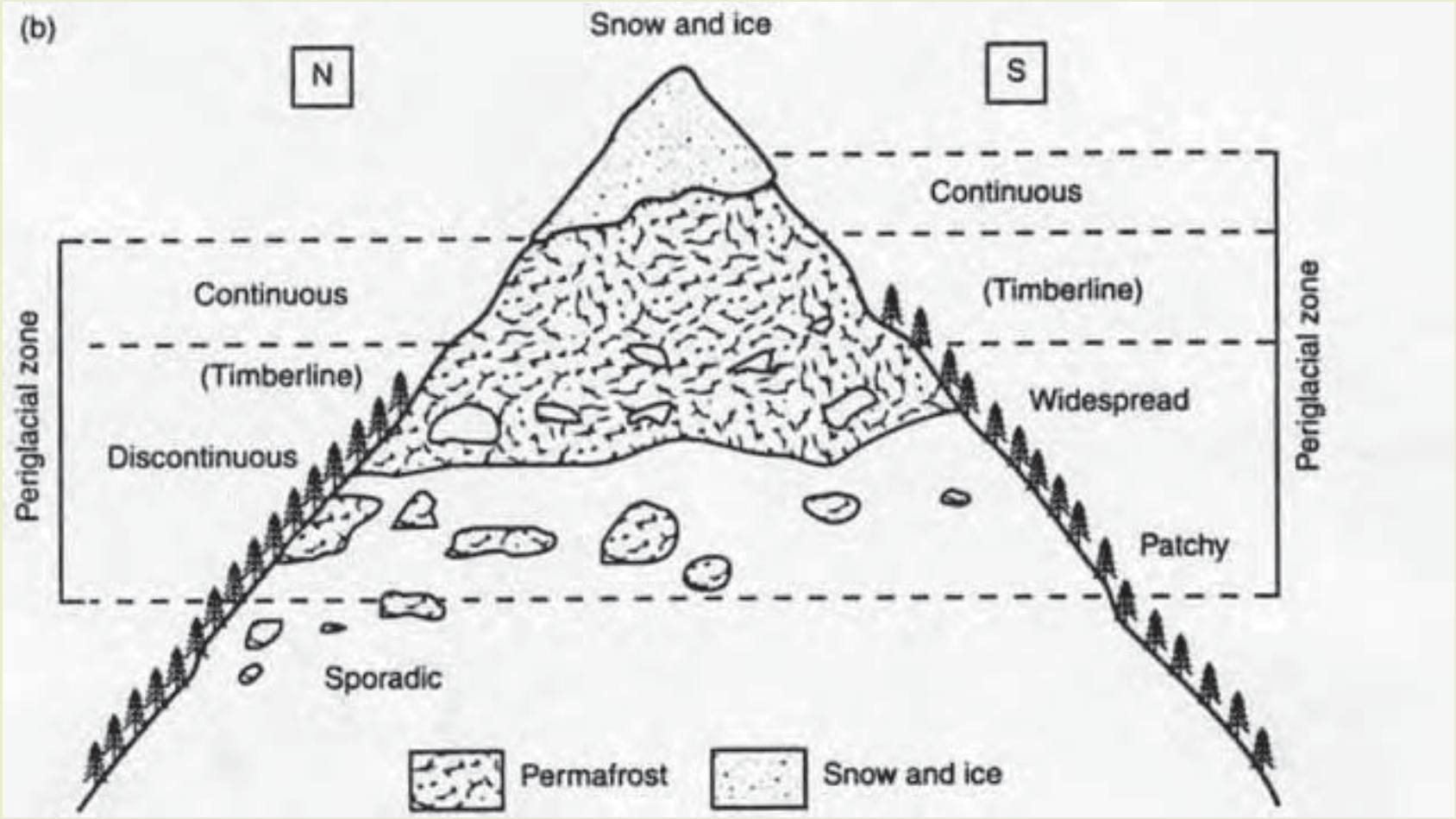
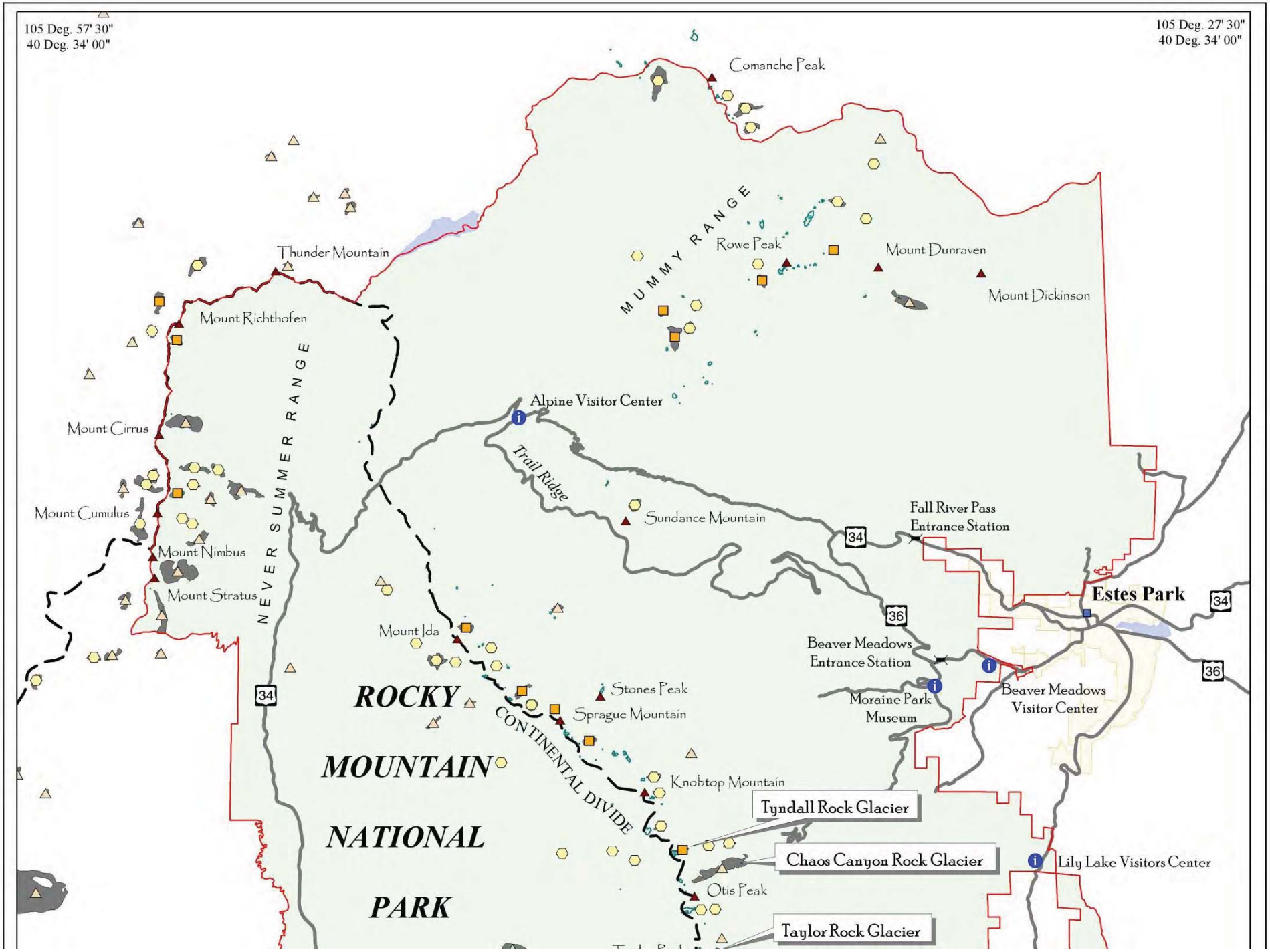


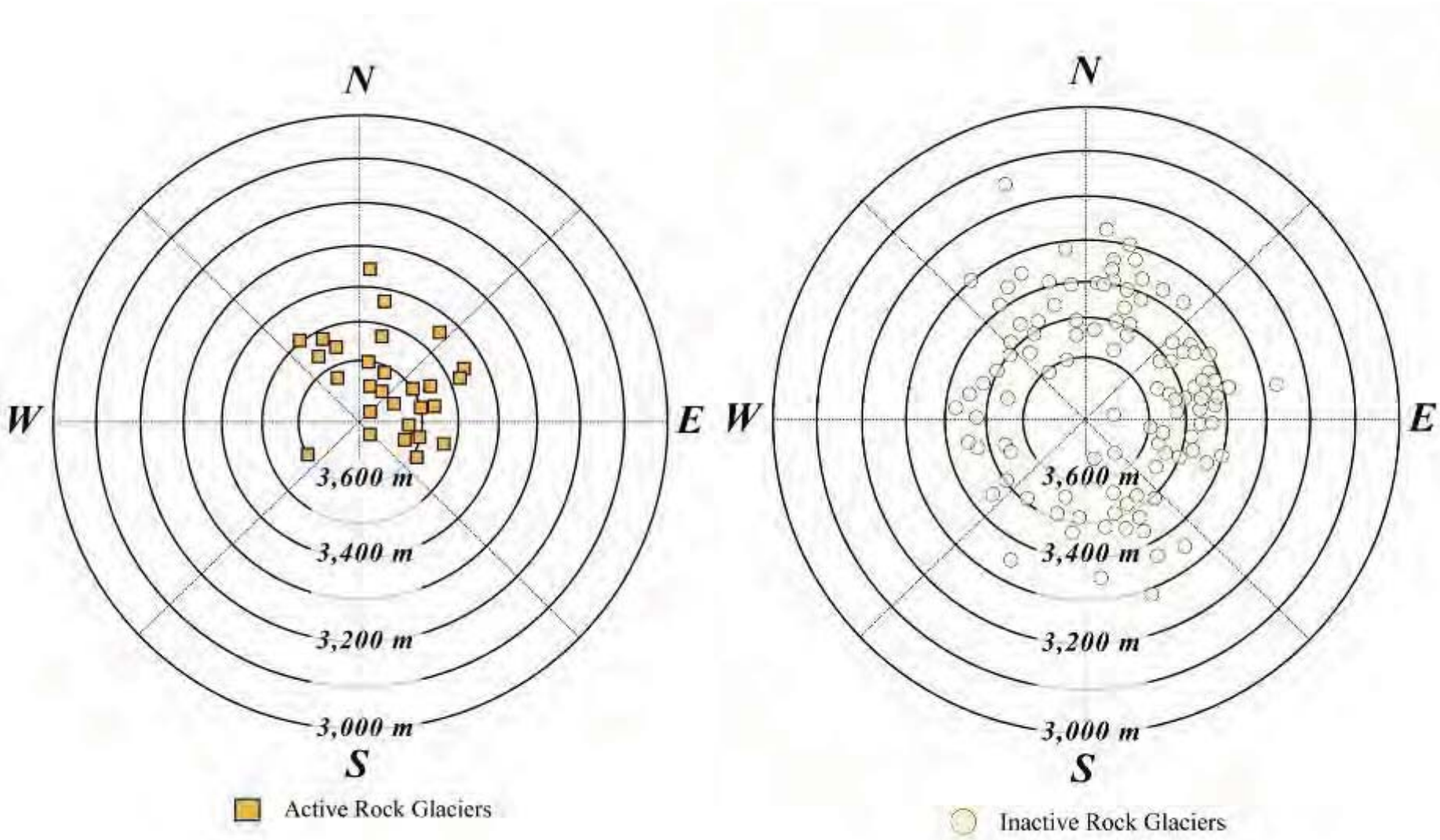
FIGURE 6.1 Distribution of permafrost in the northern hemisphere. (Modified from Péwé, 1983)



Mountain Permafrost

The Periglacial Environment


105 Deg. 57' 30"
40 Deg. 34' 00"
105 Deg. 27' 30"
40 Deg. 34' 00"
Comanche Peak
MUMMY RANGE
Rowe Peak
Mount Dunraven
Mount Dickinson
Thunder Mountain
Mount Richthofen
NEVER SUMMER RANGE
Mount Cirrus
Alpine Visitor Center
Trail Ridge
Mount Cumulus
Sundance Mountain
Fall River Pass
Entrance Station
Mount Nimbus
Mount Stratus
34
Estes Park
34
36
Mount Ida
Beaver Meadows
Entrance Station
36
Beaver Meadows
Visitor Center
Moraine Park
Museum
Stones Peak
ROCKY
Sprague Mountain
CONTINENTAL DIVIDE
MOUNTAIN
Knobtop Mountain
Tyndall Rock Glacier
NATIONAL
Chaos Canyon Rock Glacier
Lily Lake Visitors Center
Otis Peak
PARK
Taylor Rock Glacier


N
W
E
S
3,600 m
3,400 m
3,200 m
3,000 m
Active Rock Glaciers
N
W
E
S
3,600 m
3,400 m
3,200 m
3,000 m
Inactive Rock Glaciers

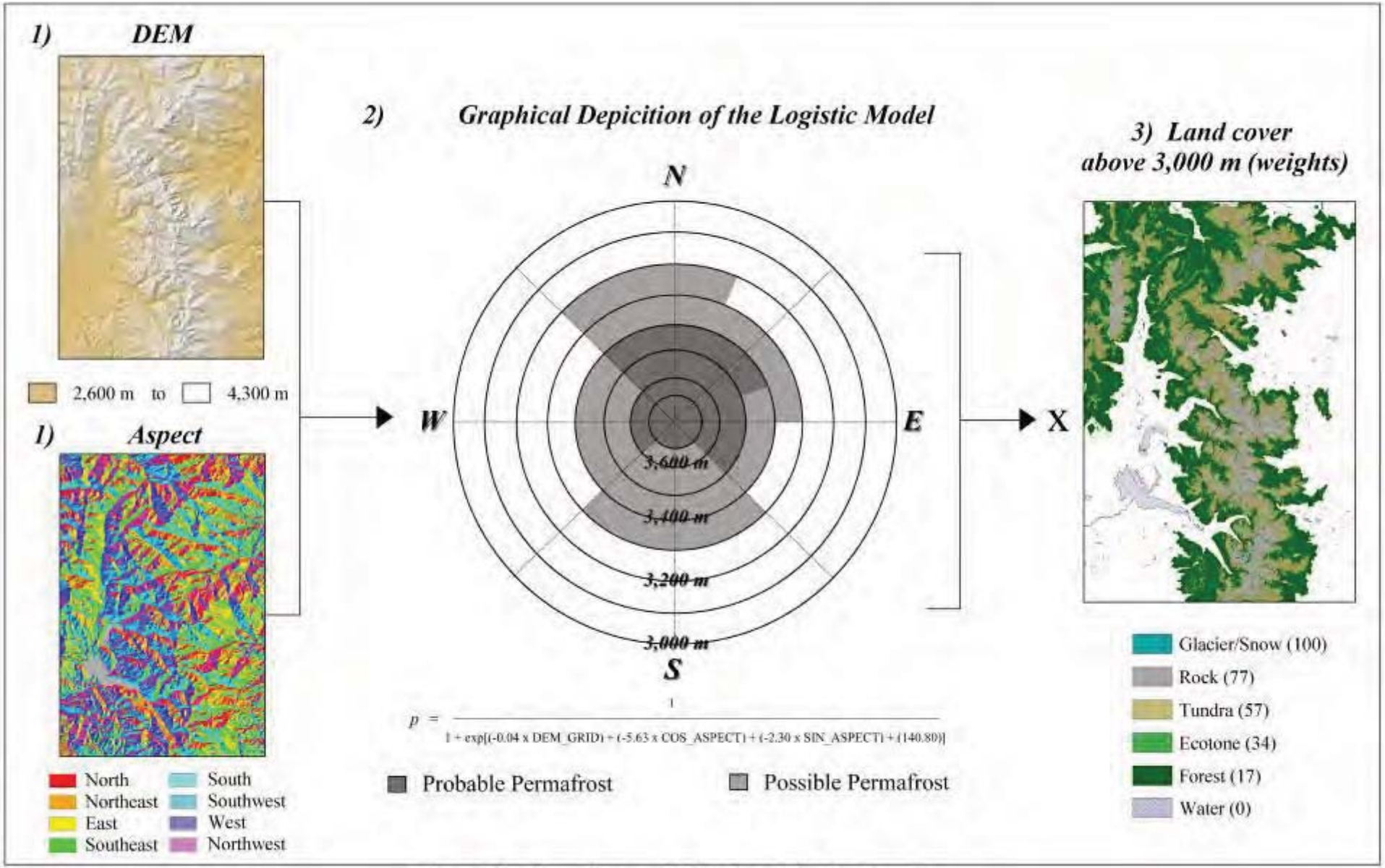
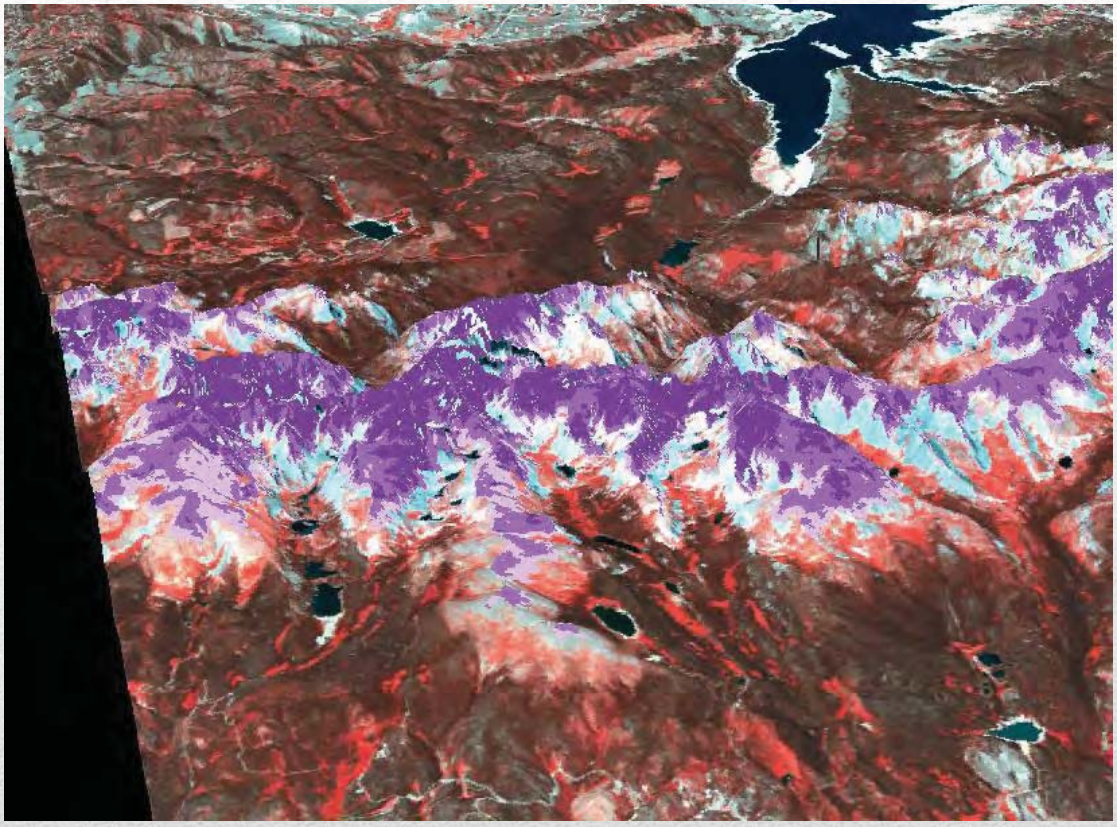


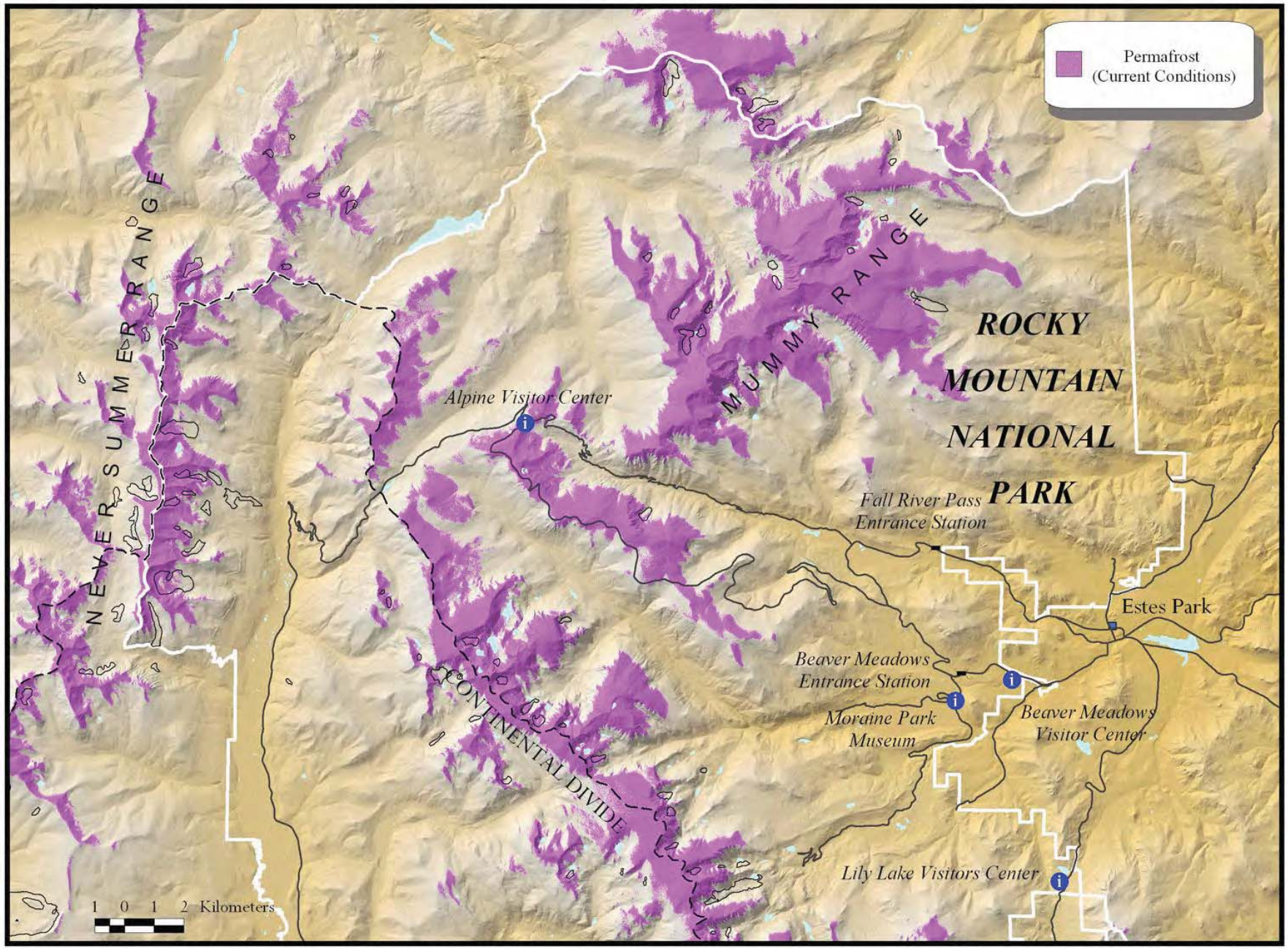
Figure 3.2 - Permafrost model developed for the Front Range.

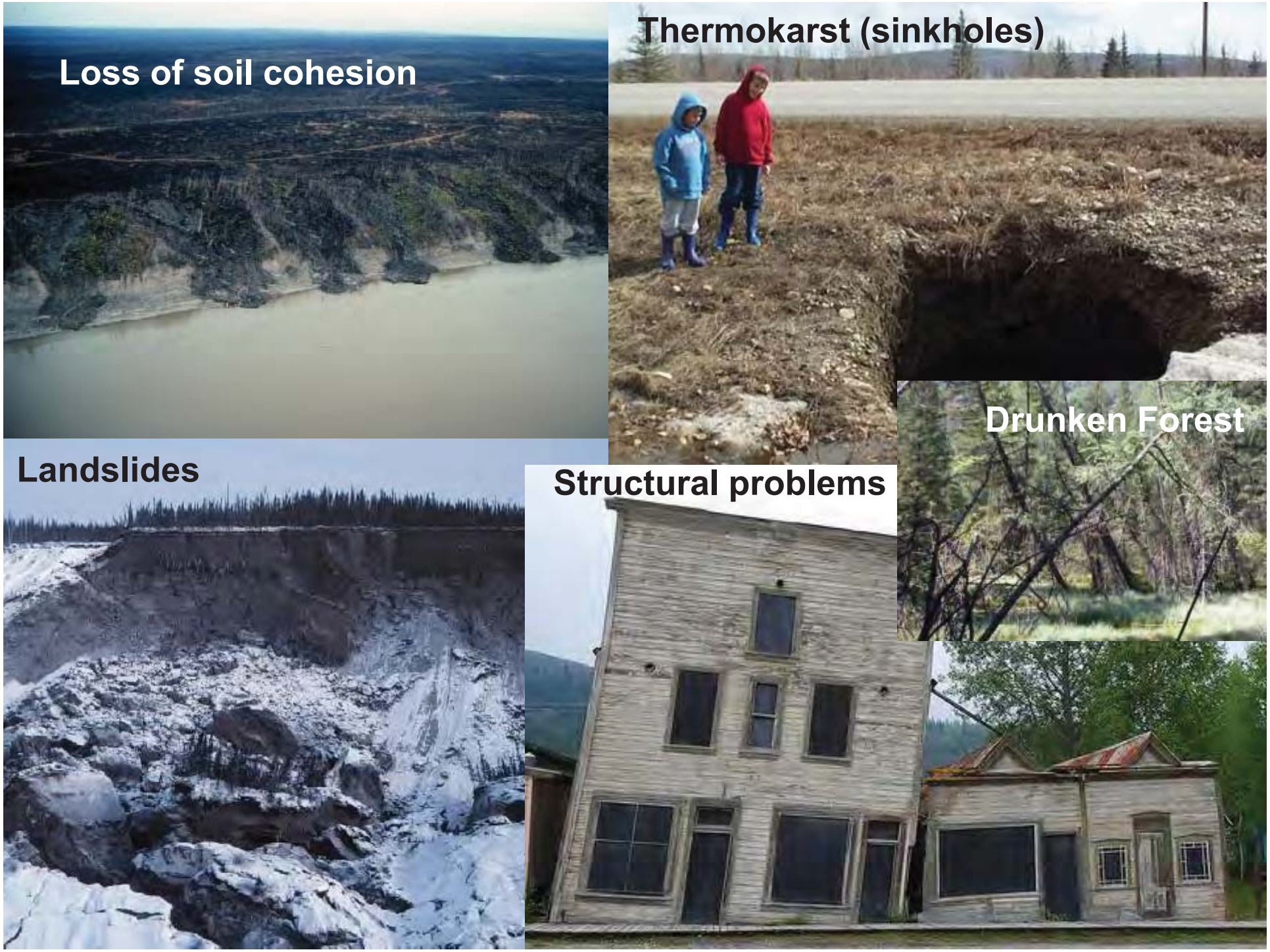


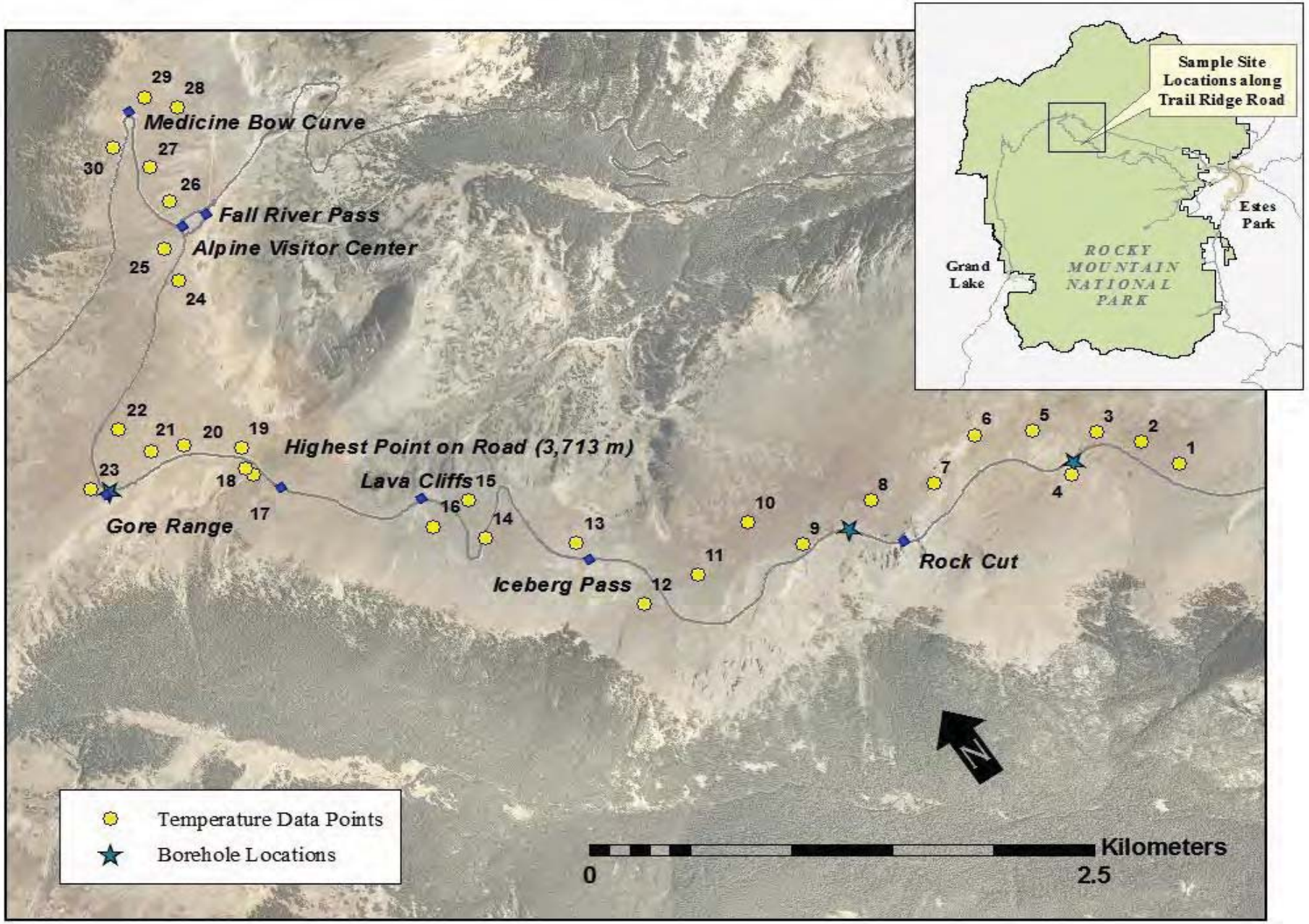
Distribution of Permafrost

Permafrost Condition	Areal Extent of Permafrost Scores Greater than 50% (km²)	Percentage of Study Area	Areal Change from Current Extent (km²)	Areal Change from Last Interval (km²)	Percent Change from Current Extent
4.0º C Cooler	2004.4	73.7%	1678.3	219.5	514.6%
3.5º C Cooler	1784.9	65.6%	1458.8	195.5	447.3%
3.0º C Cooler	1589.4	58.4%	1263.3	202.0	387.4%
2.5º C Cooler	1387.4	51.0%	1061.3	221.5	325.5%
2.0º C Cooler	1166.0	42.8%	839.8	227.0	257.5%
1.5º C Cooler	939.0	34.5%	612.9	230.3	187.9%
1.0º C Cooler	708.6	26.0%	382.5	213.2	117.3%
0.5º C Cooler	495.5	18.2%	169.4	169.4	51.9%
Current Condition	**326.1**	**12.0%**	**-----**	**-----**	**-----**
0.5º C Warmer	191.4	7.0%	-134.7	-134.7	-41.3%
1.0º C Warmer	100.9	3.7%	-225.2	-90.5	-69.1%
1.5º C Warmer	47.8	1.8%	-278.3	-53.1	-85.3%
2.0º C Warmer	19.9	0.7%	-306.2	-27.9	-93.9%
2.5º C Warmer	6.7	0.2%	-319.4	-13.1	-97.9%
3.0º C Warmer	1.9	0.1%	-324.2	-4.8	-99.4%
3.5º C Warmer	0.3	0.0%	-325.8	-1.5	-99.9%
4.0º C Warmer	0.1	0.0%	-326.0	-0.3	-100.0%

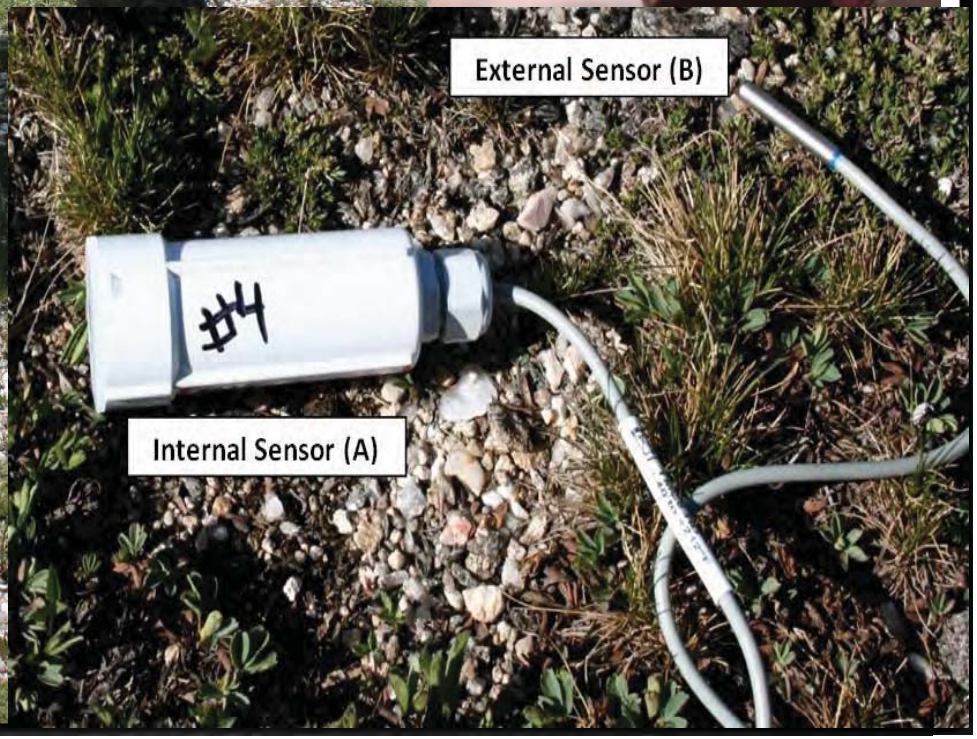
CURRENT


Permafrost
(Current Conditions)
NEVER SUMMER RANGE
MUMMY RANGE
ROCKY MOUNTAIN NATIONAL PARK
Alpine Visitor Center
Fall River Pass Entrance Station
Estes Park
Beaver Meadows Entrance Station
Moraine Park Museum
Beaver Meadows Visitor Center
CONTINENTAL DIVIDE
Lily Lake Visitors Center
1 0 1 2 Kilometers

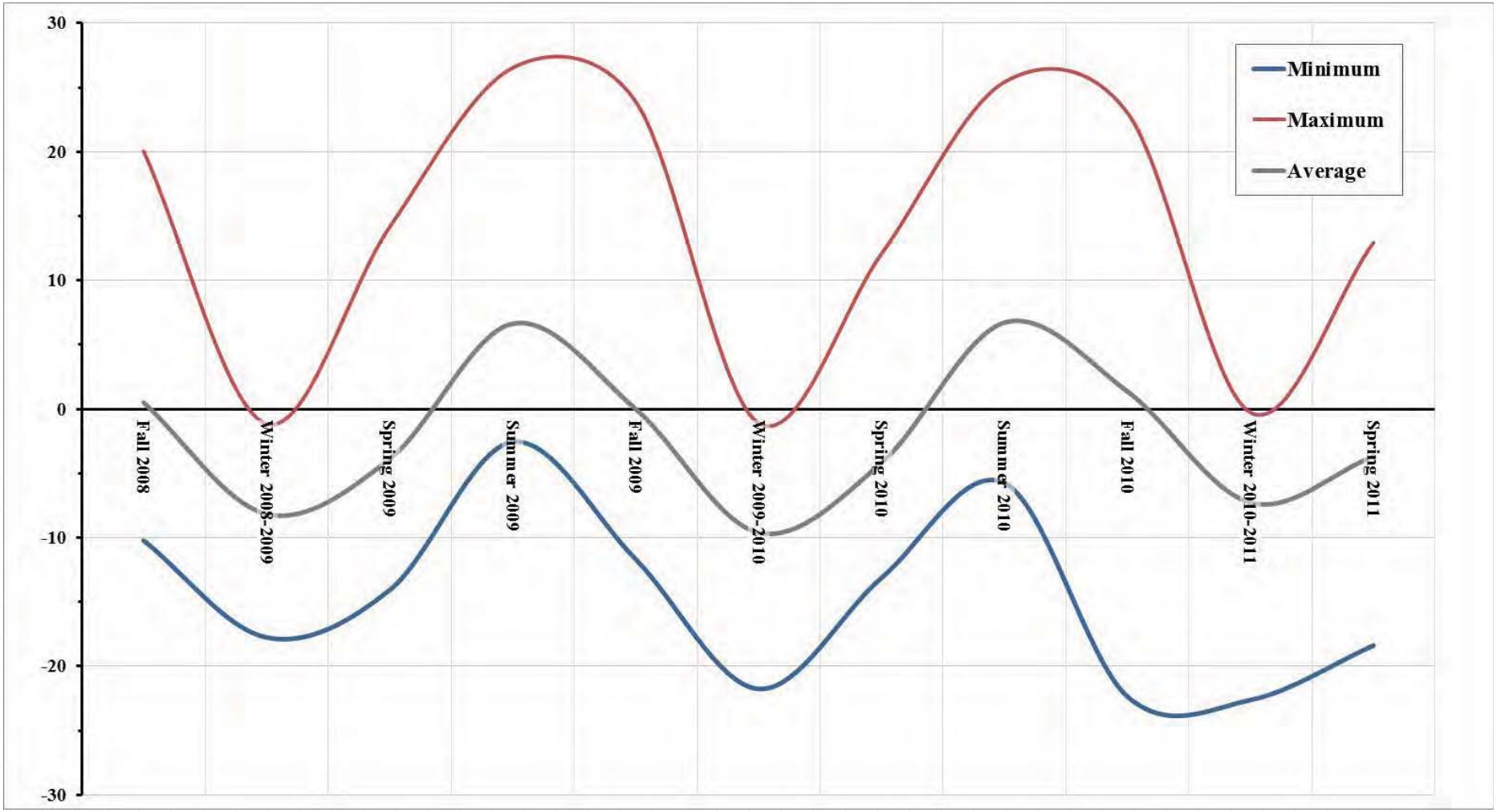

Loss of soil cohesion
Thermokarst (sinkholes)
Drunken Forest
Landslides
Structural problems


Sample Site Locations along Trail Ridge Road
Grand Lake
ROCKY MOUNTAIN NATIONAL PARK
Estes Park
Medicine Bow Curve
Fall River Pass
Alpine Visitor Center
Highest Point on Road (3,713 m)
Lava Cliffs
Gore Range
Iceberg Pass
Rock Cut
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
Temperature Data Points
Borehole Locations
N
0
2.5
Kilometers

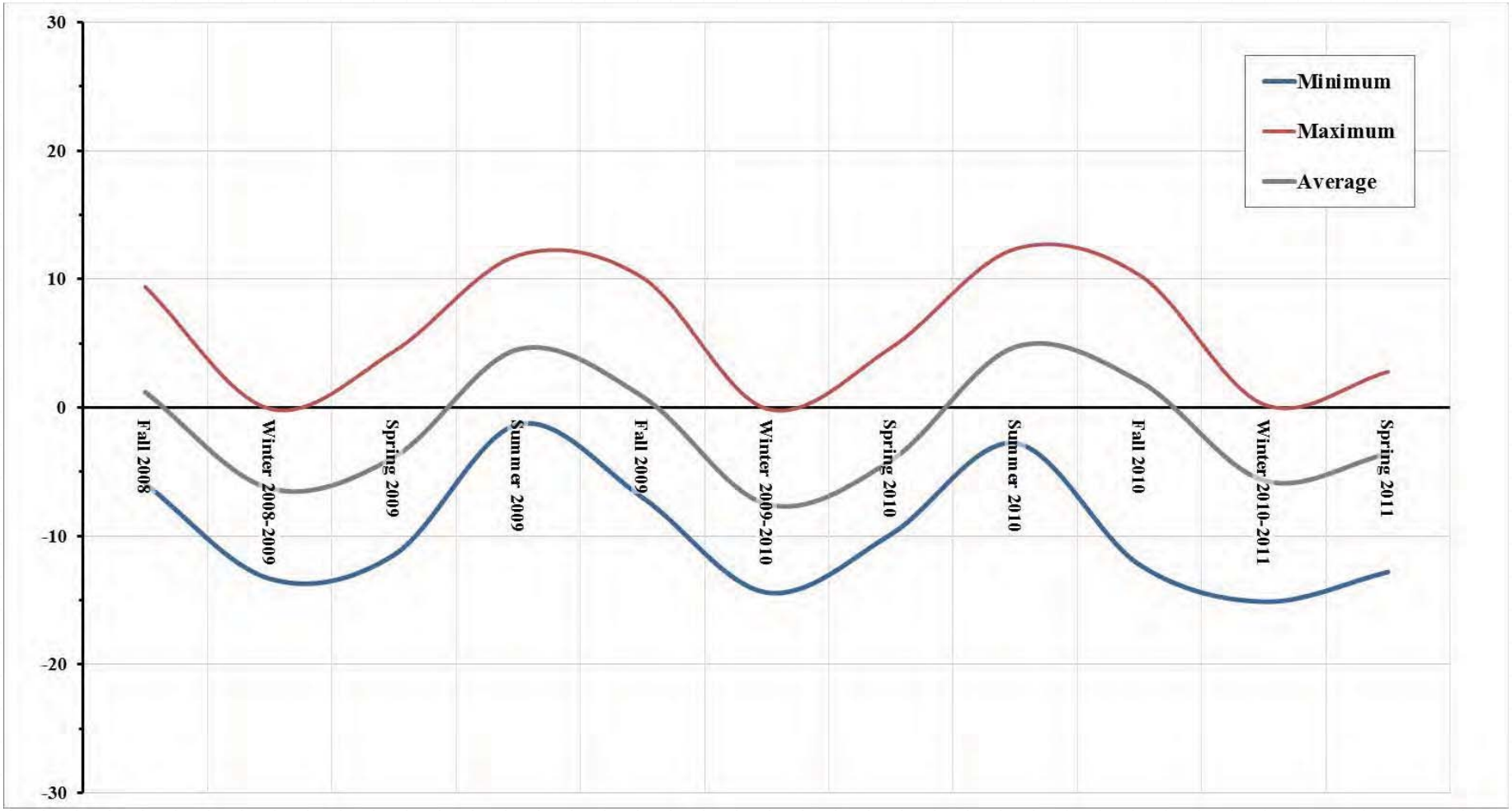
Monitoring Methods



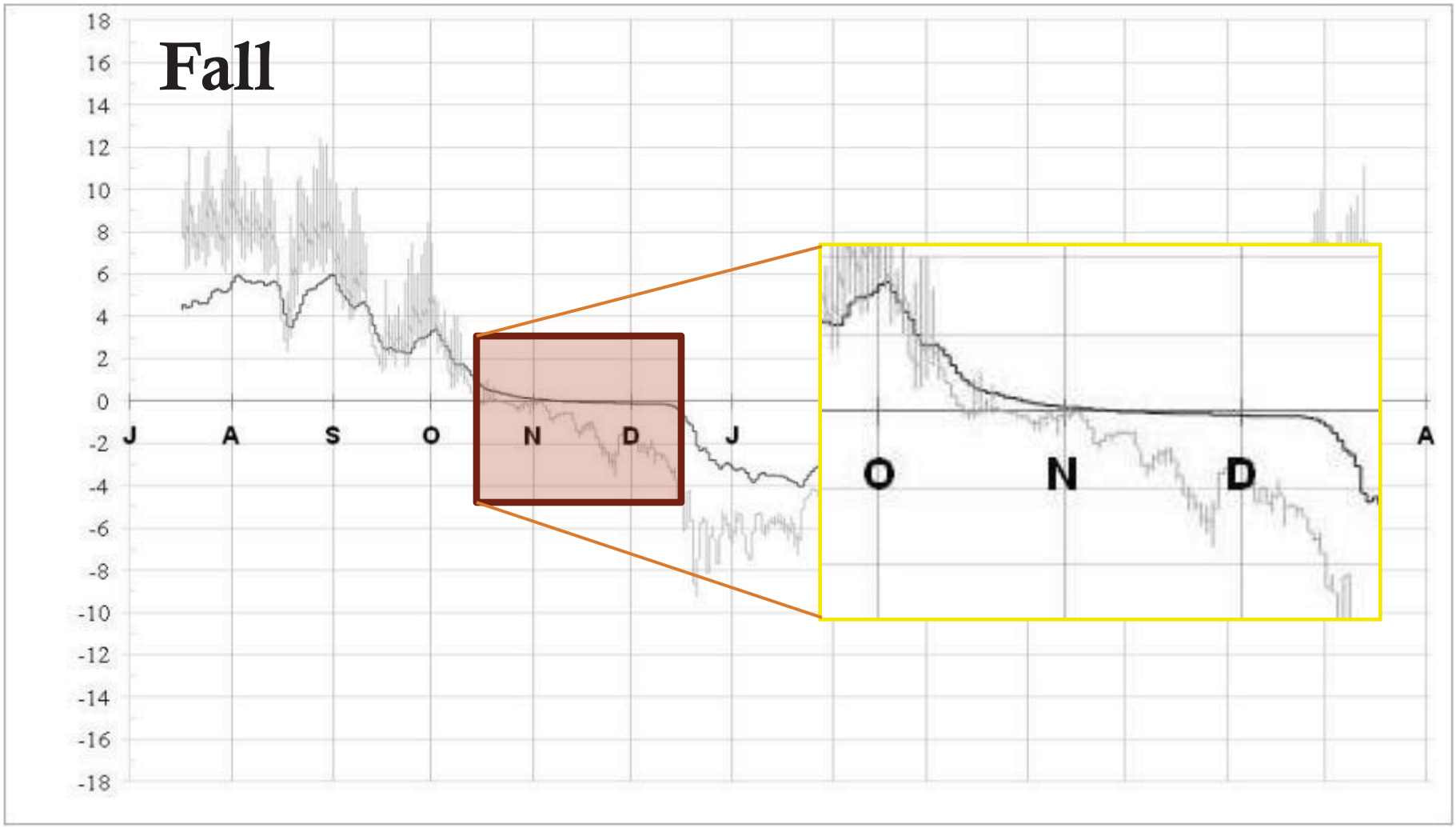
Surface Temperature



Deeper Temperature

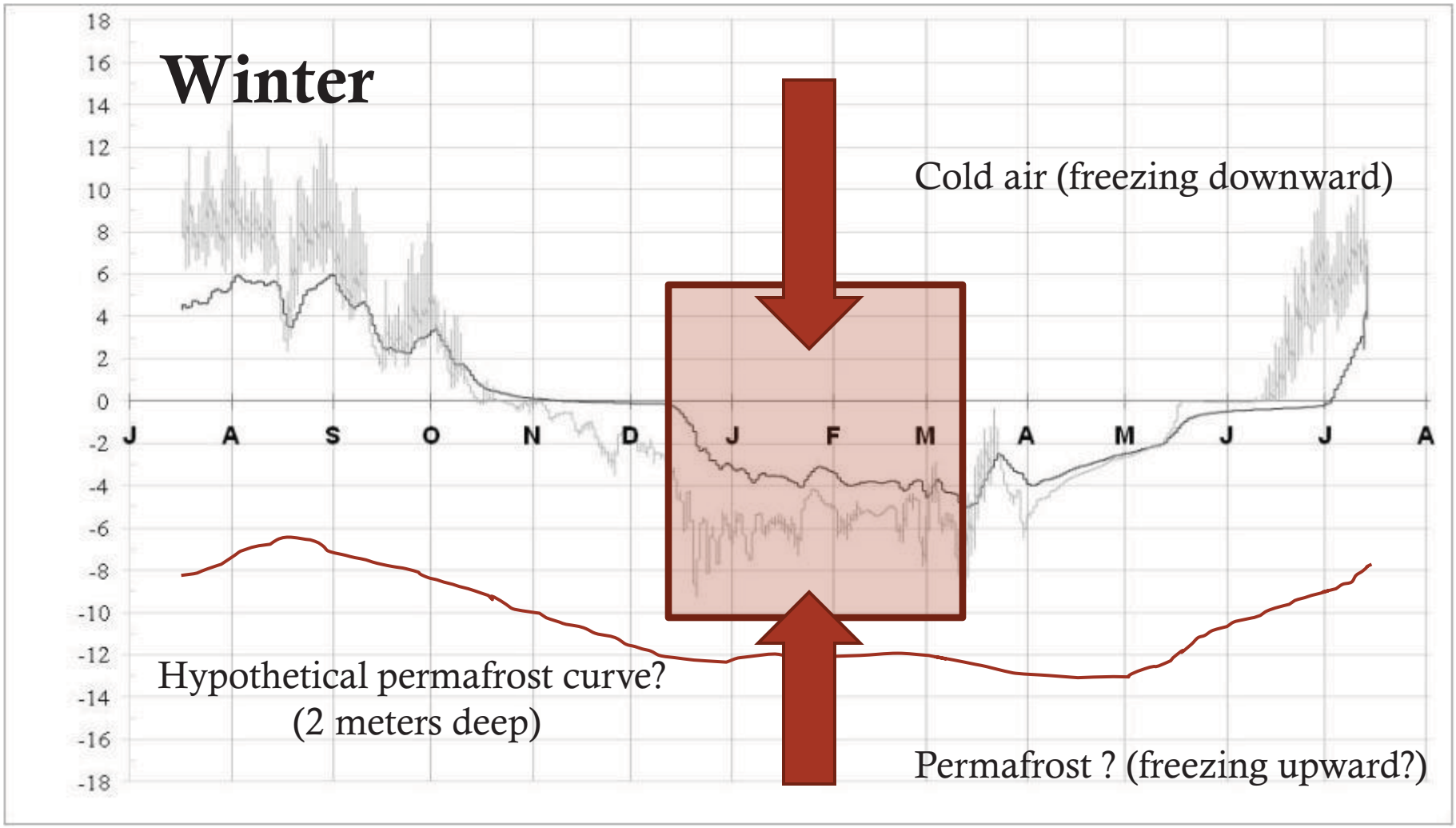


Point	Site Description	Aspect (Direction)	Elevation (m)	Slope (°)
11	Center of rock wedge	NNW	3647	8



The energy balance becomes negative in the Fall

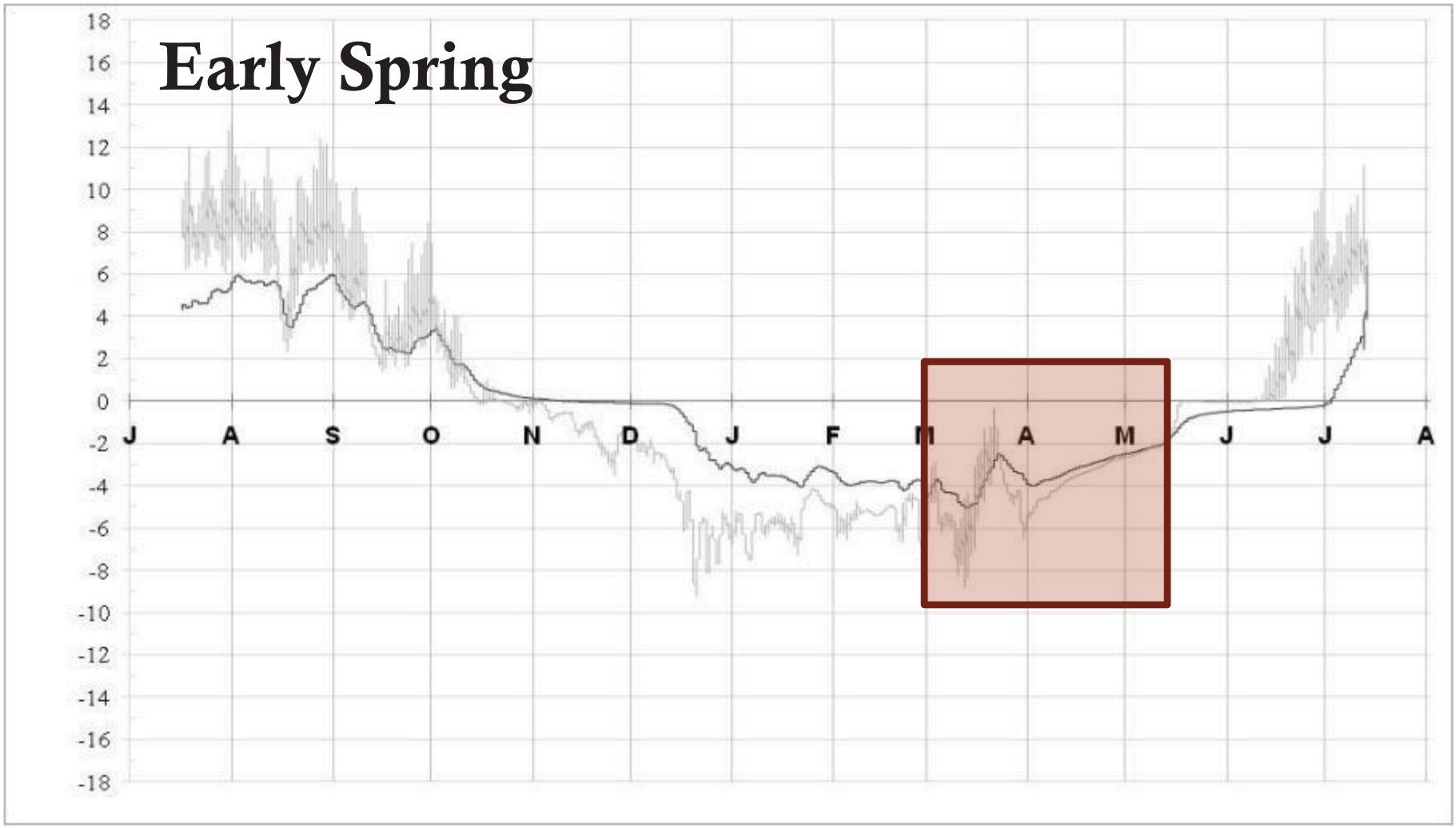
- Soil freezes from the surface (surface soil is colder)
- Latent heat is released (warms the soil)
- Results in an isothermal plateau or the *zero curtain*



Soil water is frozen as temperature remains below 0° C

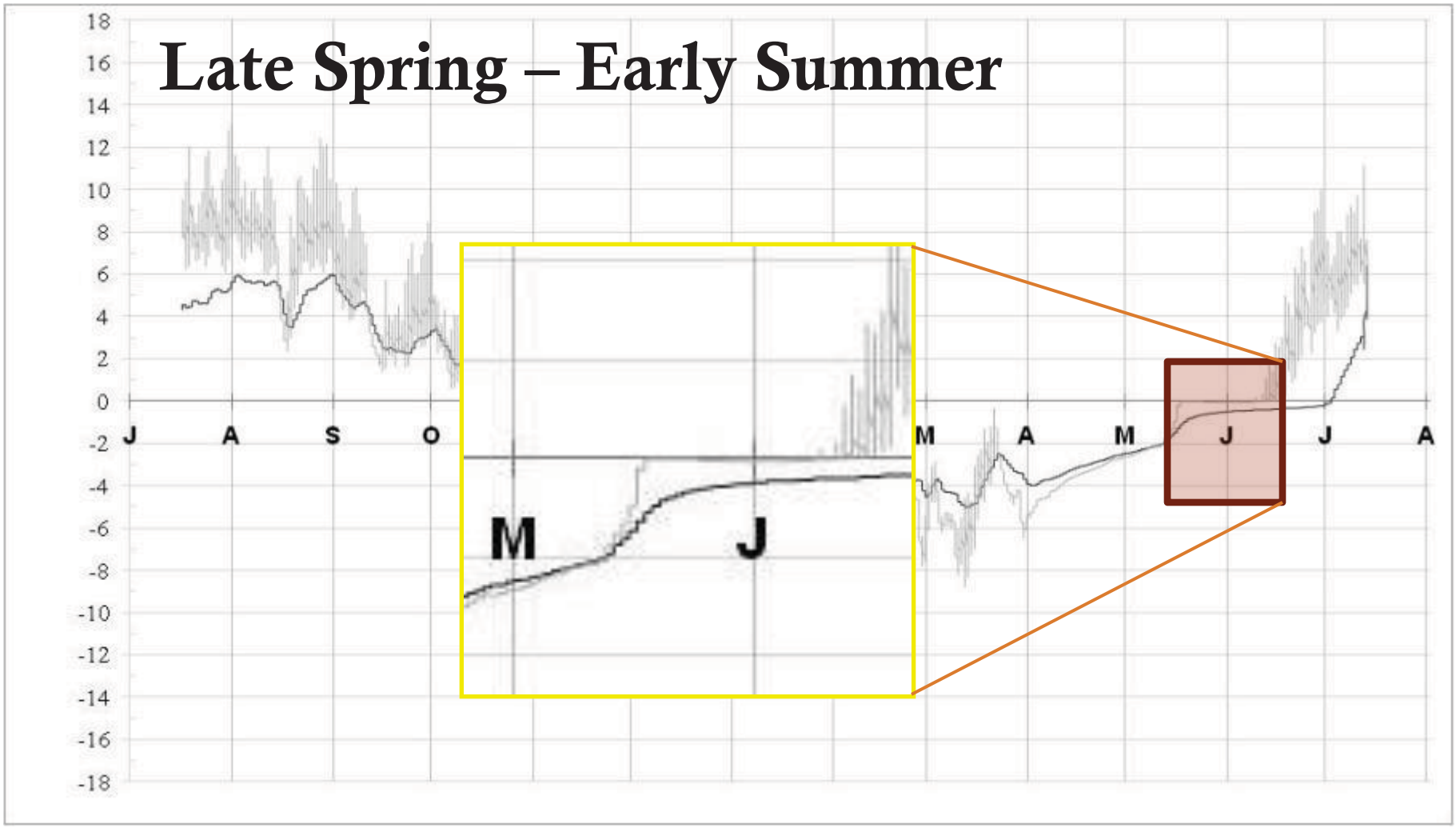
Freezing fronts advance from the surface and at depth to freeze the active layer

Surface is colder than at depth – really cold winters!!

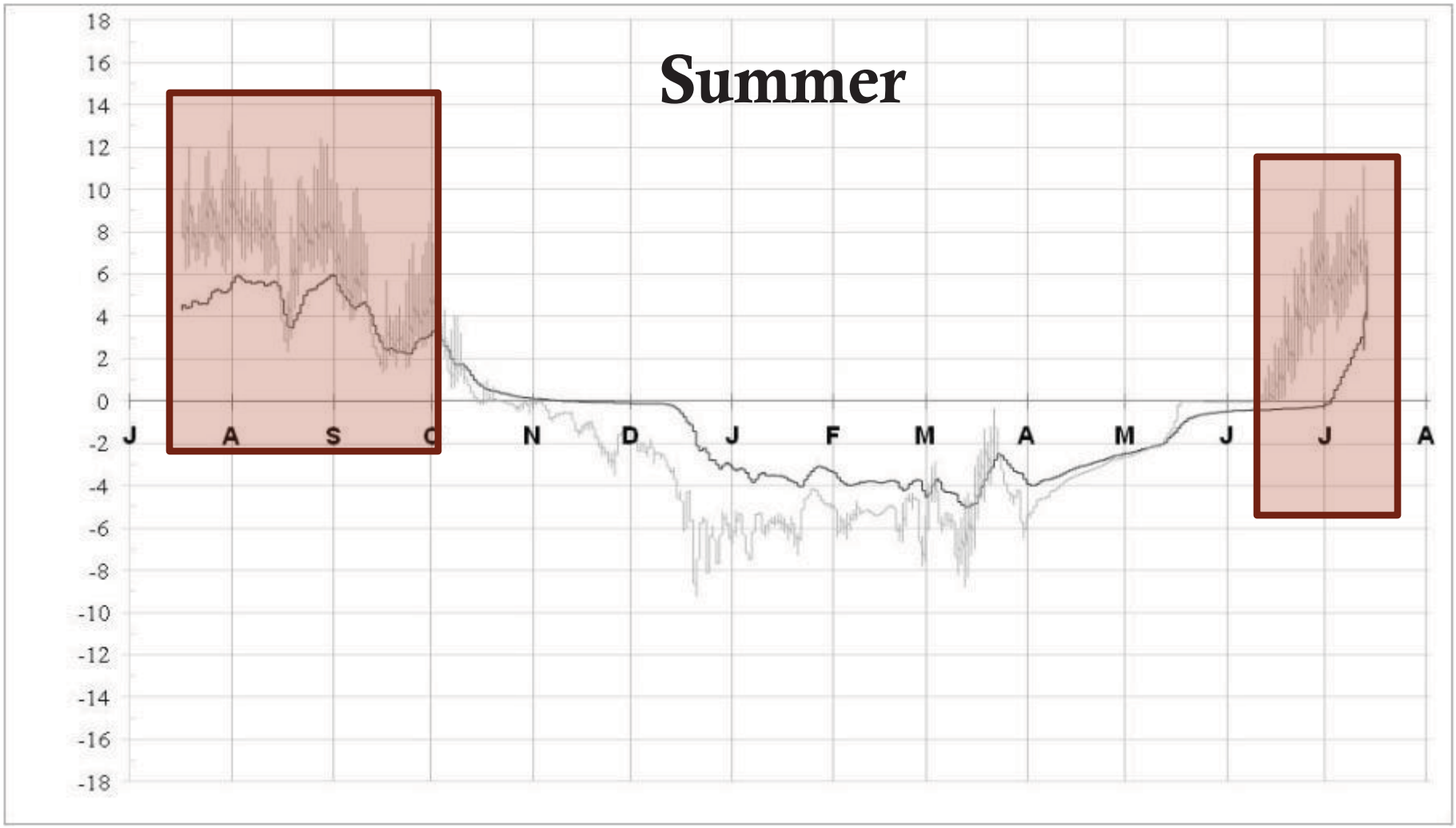


Surface starts to warm and becomes warmer than the deeper probe

Late Spring – Early Summer



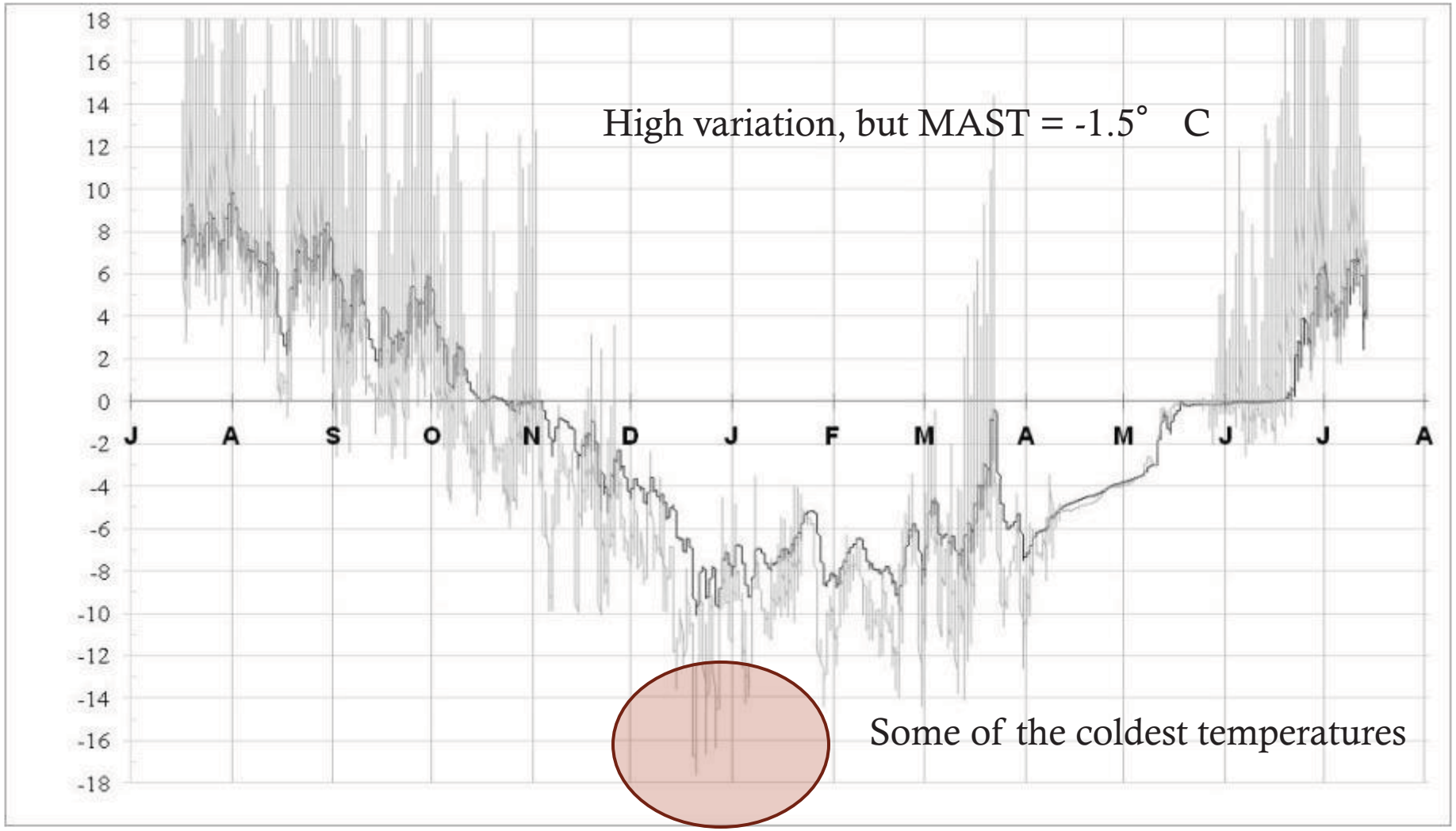
Thawing front advances from the surface
- Latent heat is absorbed (keeps soil cold)
- Temperatures remain at or slightly below 0° C

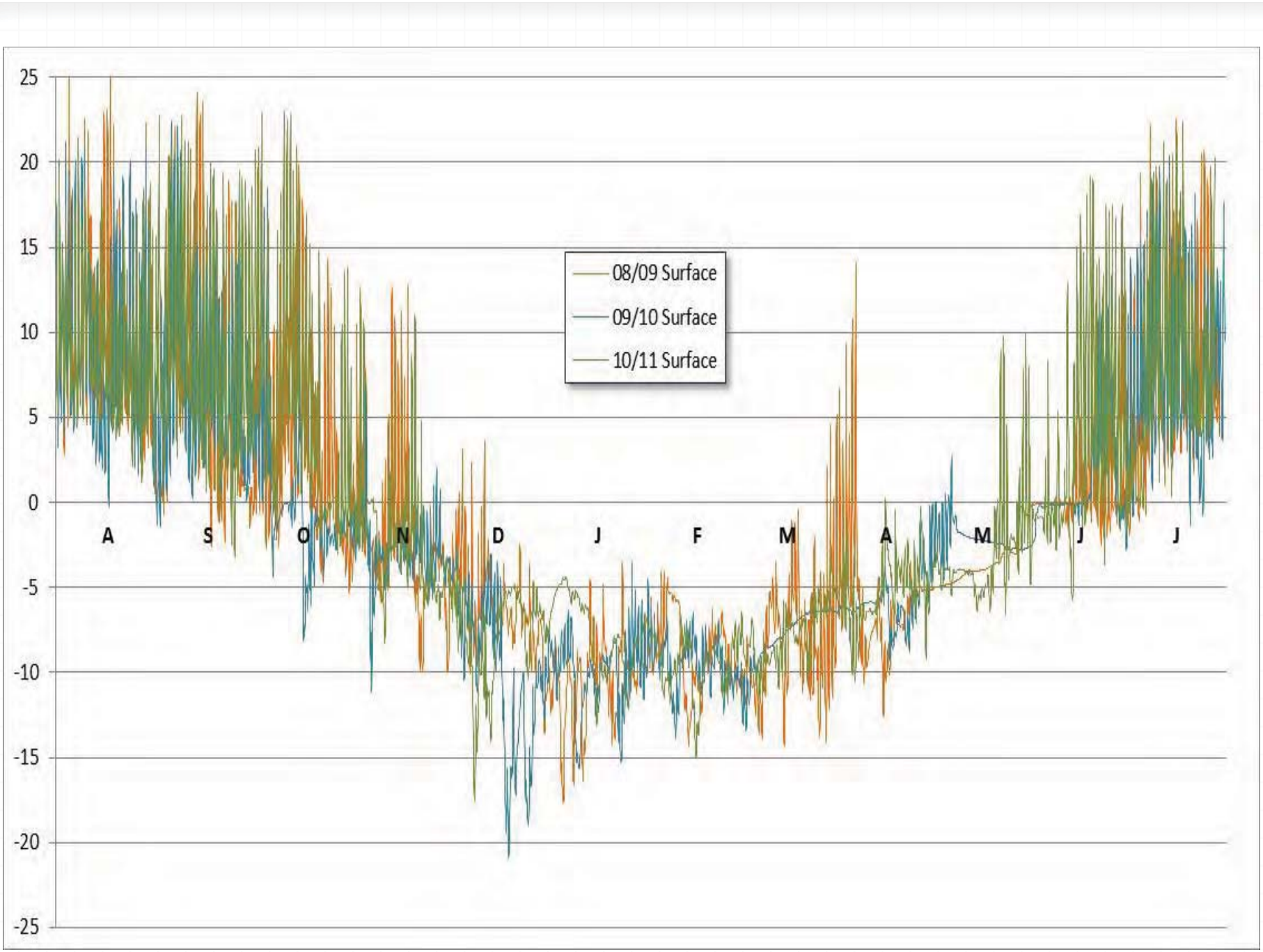


Ground temperatures rise quickly through July and stabilize in August
The surface probe shows more extreme daily variation

Point	Site Description	Aspect (Direction)	Elevation (m)	Slope (°)
1	Rock wedge	SW	3688	19

Site 1 – Balch Ventilation



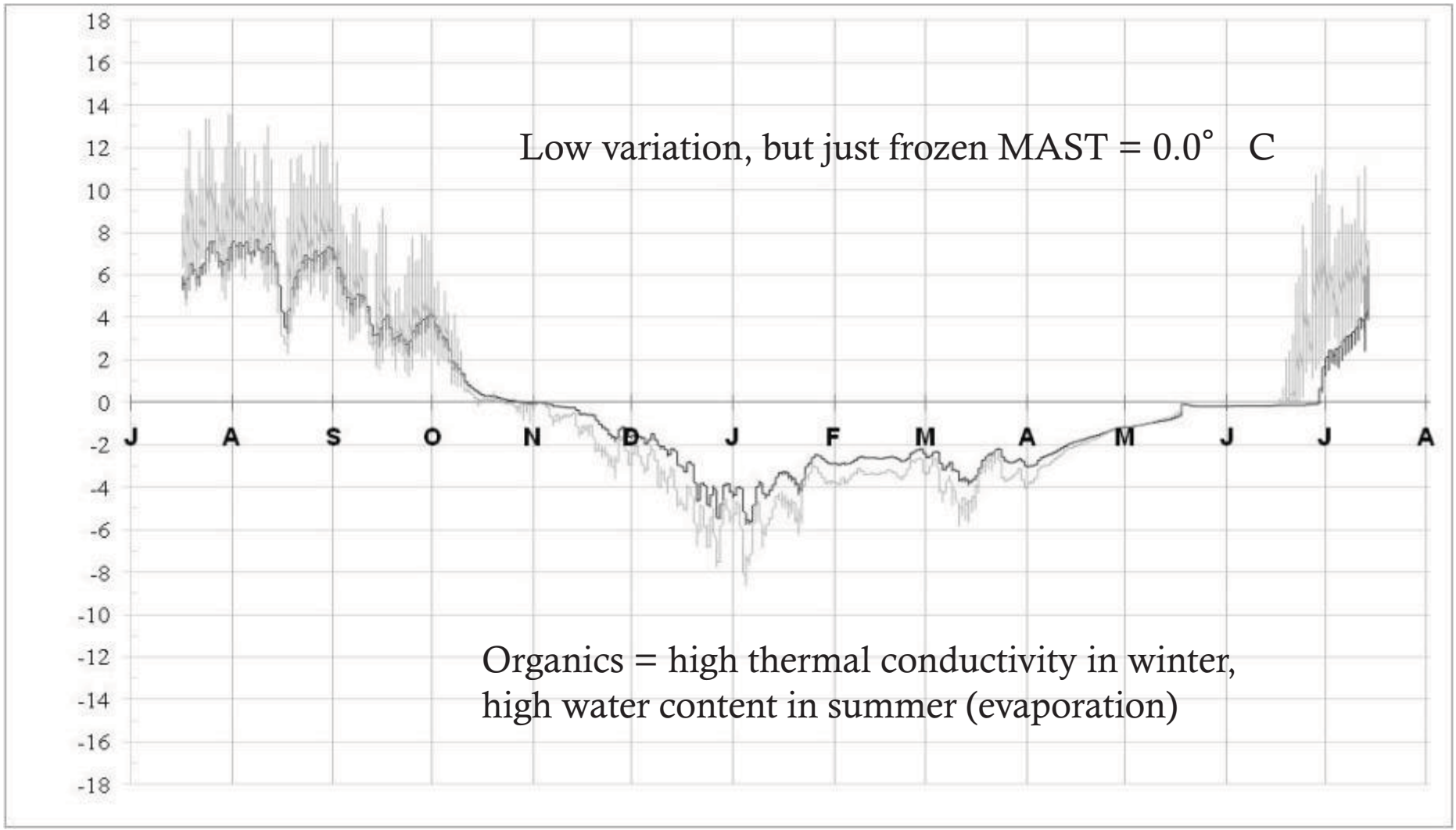

25
20
15
10
5
0
-5
-10
-15
-20
-25
A
S
O
N
D
J
F
M
A
M
J
J
08/09 Surface
09/10 Surface
10/11 Surface

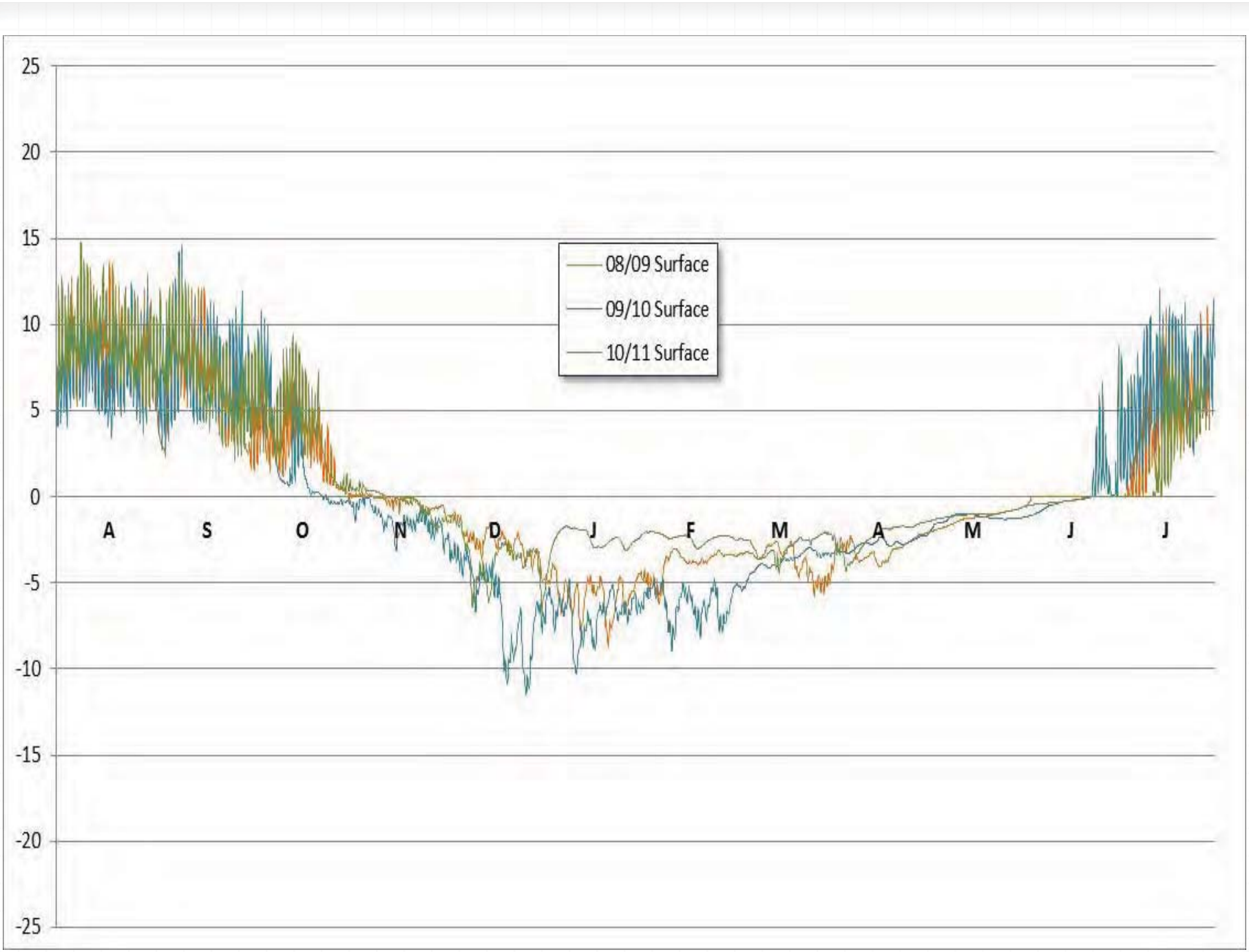

25
20
15
10
5
0
-5
-10
-15
-20
-25
A
S
O
N
D
J
F
M
A
M
J
J
08/09 Deeper
09/10 Deeper
10/11 Deeper

0.5 km from Site 1, but extremely different…

Point	Site Description	Aspect (Direction)	Elevation (m)	Slope (°)
3	Earth hummock	SSW	3684	4

Site 3 – Organic Soils




25
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10
5
0
-5
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-15
-20
-25
A
S
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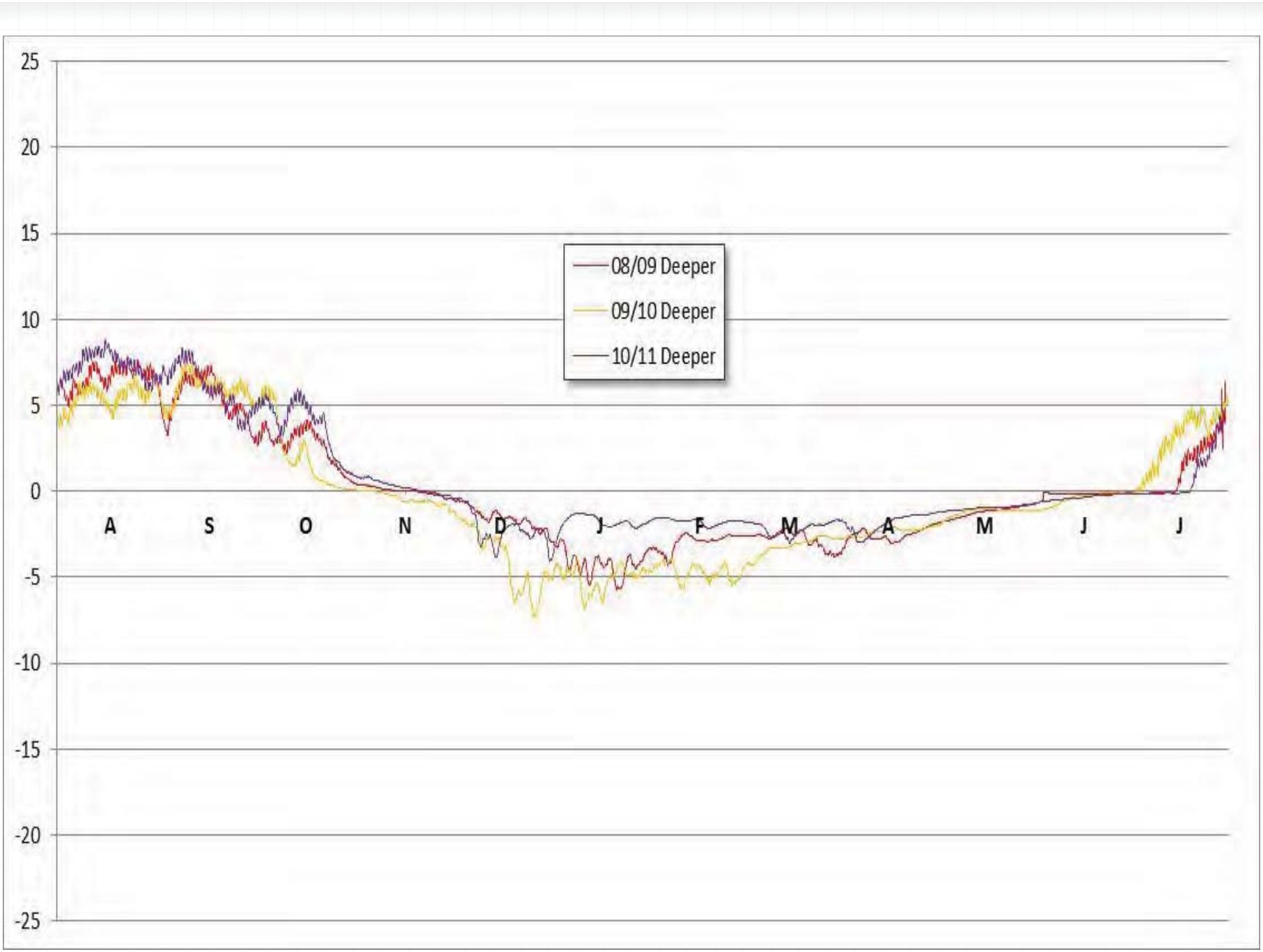
F
M
A
M
J
J
08/09 Surface
09/10 Surface
10/11 Surface


25
20
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5
0
-5
-10
-15
-20
-25
A
S
O
N
D
J
F
M
A
M
J
J
08/09 Deeper
09/10 Deeper
10/11 Deeper

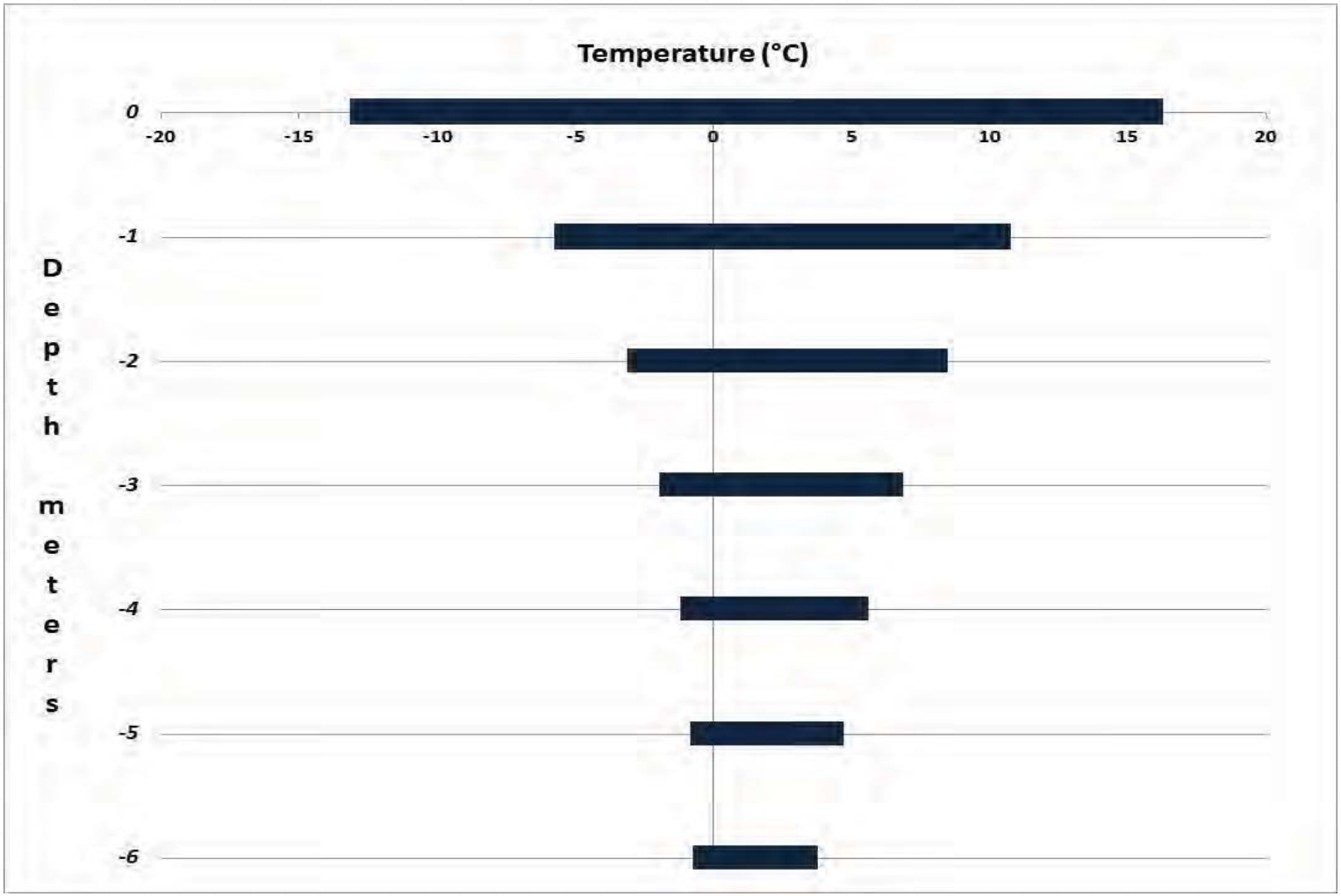
Yearly and Seasonal Temperature

		mid-July 2008 to mid-July 2009	mid-July 2009 to mid-July 2010	mid-July 2010 to mid-July 2011	Fall 2008	Winter 2008-2009	Spring 2009	Summer 2009	Fall 2009	Winter 2009-2010	Spring 2010	Summer 2010	Fall 2010	Winter 2010-2011	Spring 2011
Surface Temperature (°C)	**Average**	-1.2	-1.7	-0.6	0.5	-8.2	-3.9	6.6	0.0	-9.6	-4.2	6.7	1.4	-7.3	-3.7
	Standard Deviation	6.4	7.0	6.8	3.7	2.6	3.1	3.9	4.4	2.4	2.9	4.4	5.5	3.7	2.7
	Minimum	-17.8	-21.8	-22.6	-10.2	-17.8	-14.1	-2.6	-11.7	-21.8	-13.1	-5.8	-22.4	-22.6	-18.4
	Maximum	26.1	26.5	25.4	20.0	-1.2	14.1	26.5	23.9	-1.1	12.1	25.4	23.0	-0.3	12.9
Deeper Temperature (°C)	**Average**	-1.1	-1.5	-0.6	1.2	-6.3	-3.9	4.5	0.9	-7.5	-4.1	4.7	2.1	-5.7	-3.6
	Standard Deviation	4.9	5.3	5.2	2.5	2.2	2.2	2.9	3.1	2.1	2.4	3.4	3.7	3.2	2.2
	Minimum	-13.3	-14.4	-15.1	-5.9	-13.3	-11.5	-1.3	-7.0	-14.4	-9.9	-2.8	-12.2	-15.1	-12.8
	Maximum	12.0	11.9	12.4	9.4	-0.1	4.4	11.9	10.1	-0.1	4.7	12.4	10.3	0.2	2.8

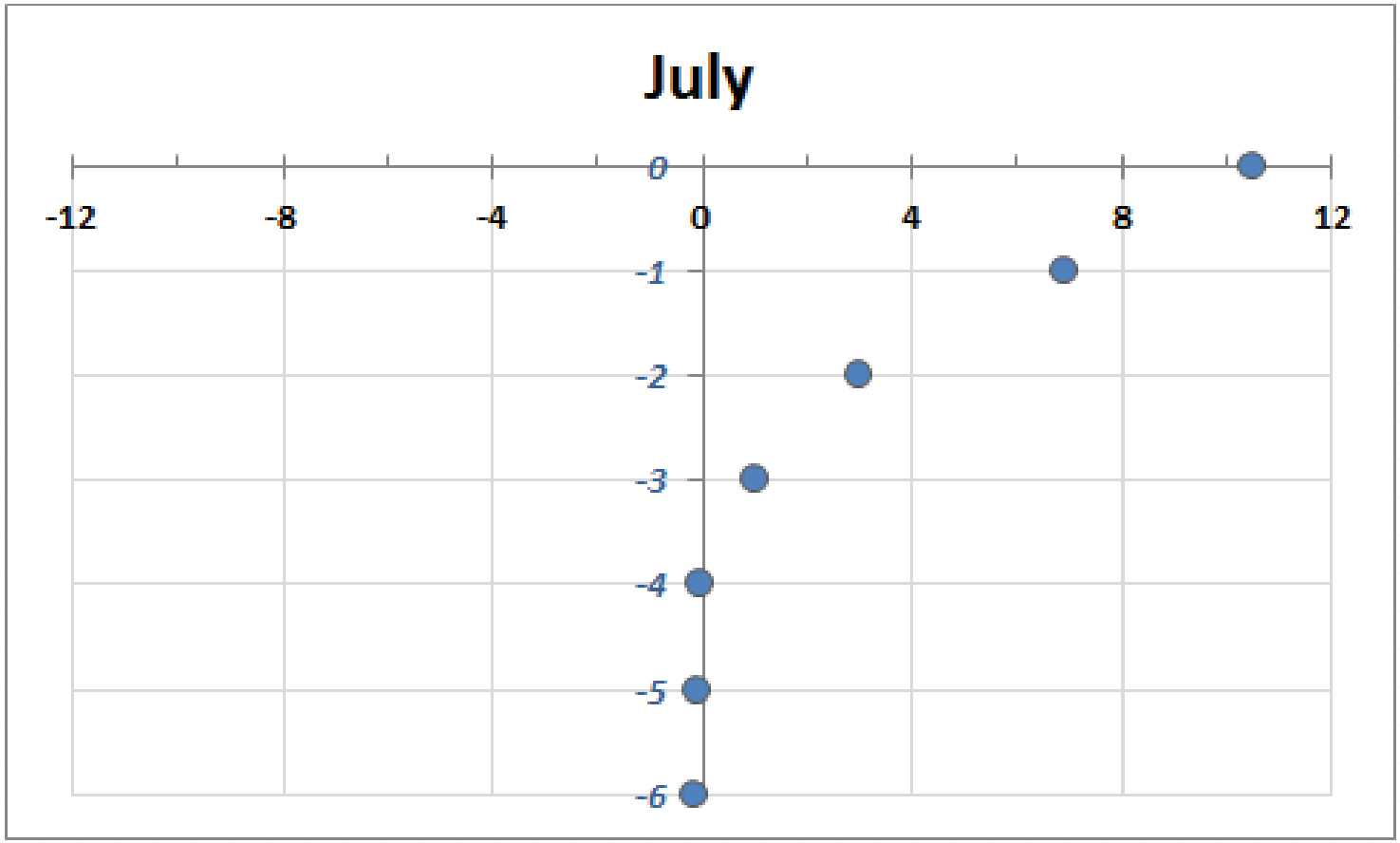
Start date at which the ground remains continuously frozen or thawed.

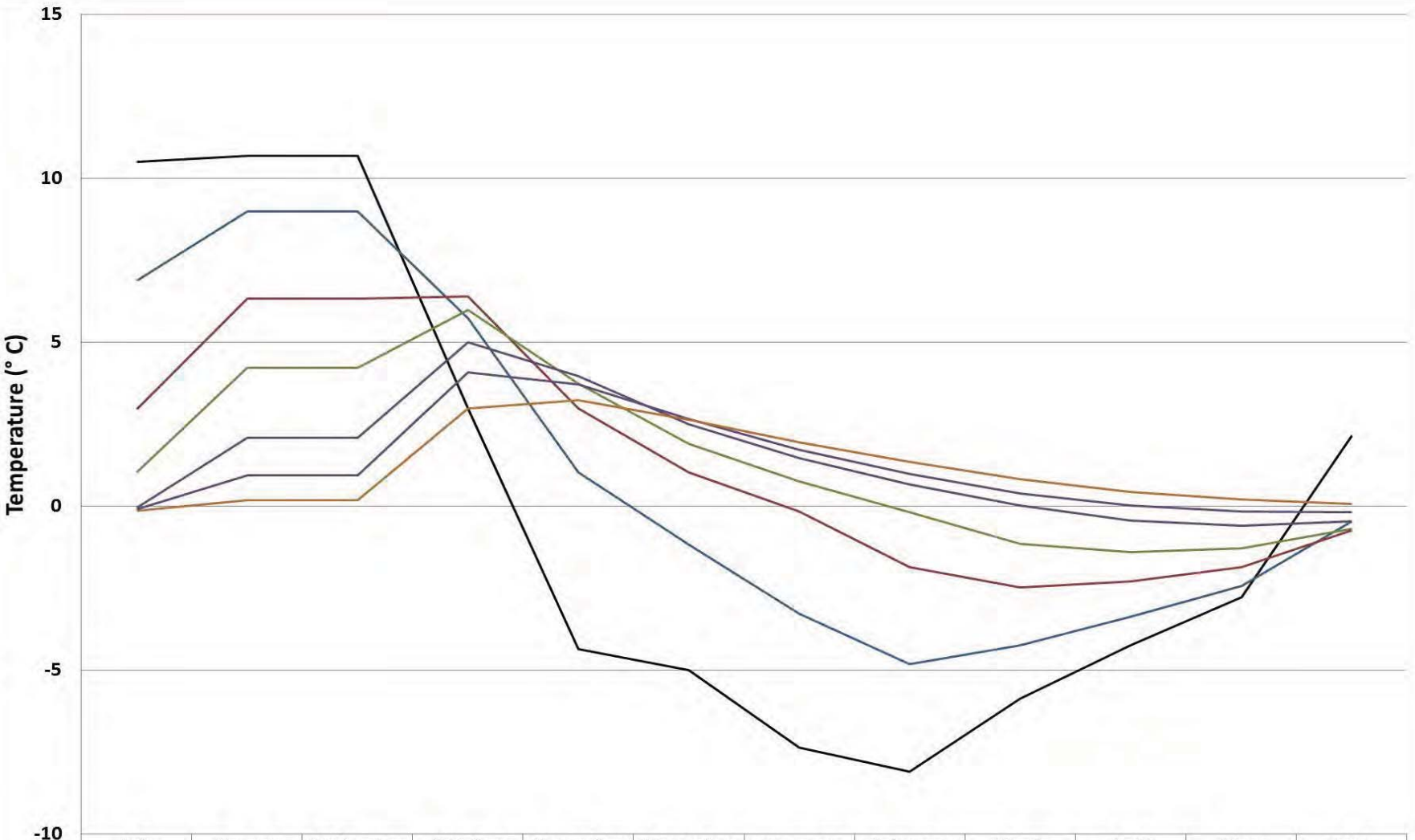
Date of:	2008 Freeze	2009 Thaw	2009 Freeze	2010 Thaw	2010 Freeze	2011 Thaw
Surface Measurement	22-Oct	21-Jun	20-Oct	19-Jun	9-Nov	18-Jun
Deeper Measurement	5-Nov	10-Jul	27-Oct	2-Jul	15-Nov	24-Jun
Lag-time (days) between the surface and deeper probes	14	19	7	14	6	6


DRILLING ENGINEERS, INC.
US DOT 439191
7HY36546
LIC. 1367

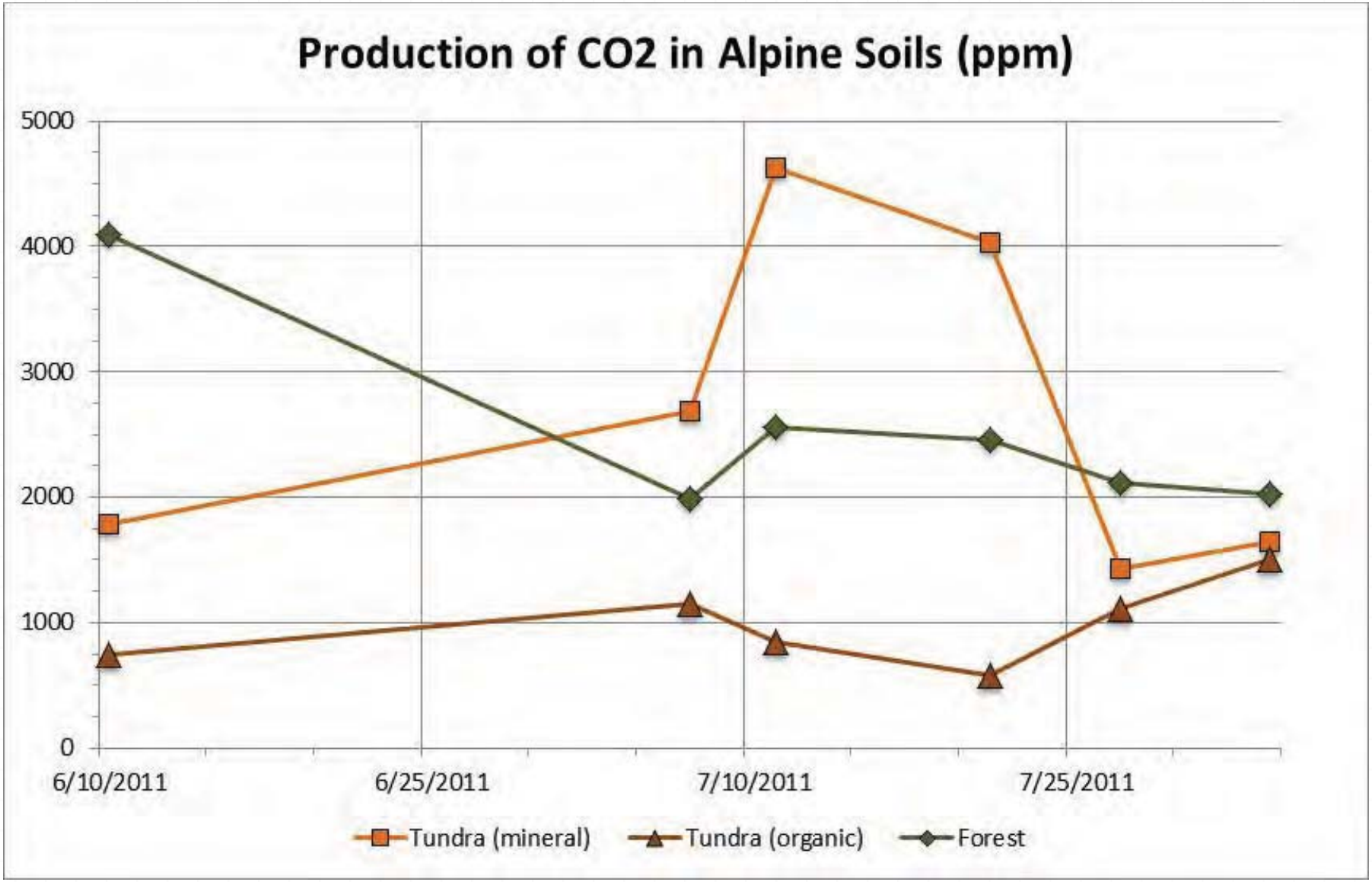


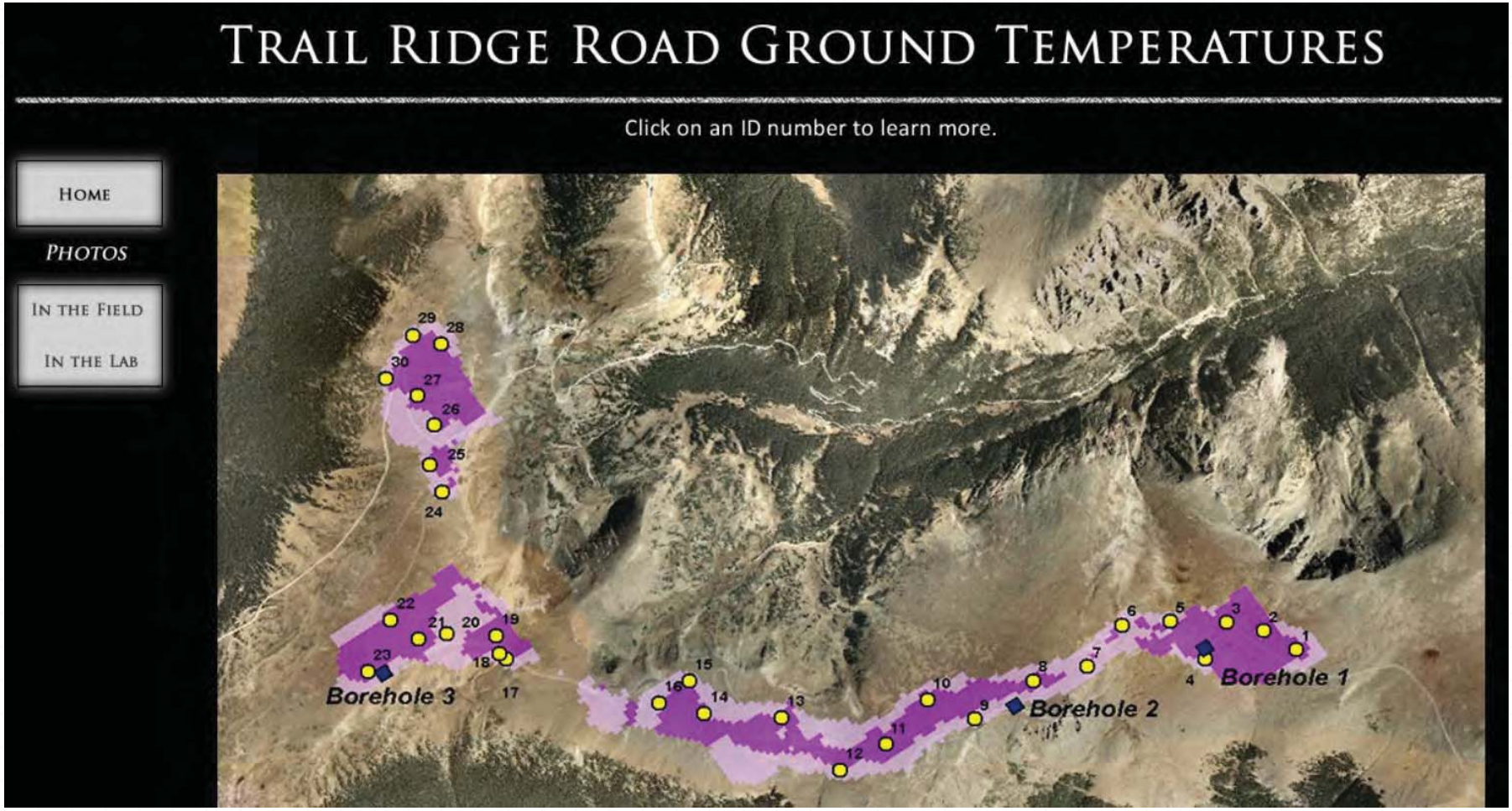
	Surface	1m	2m	3m	4m	5m	6m
Average Temperature (°C)	0.36	1.25	1.50	1.52	1.45	1.35	1.23


July
0
-1
-2
-3
-4
-5
-6
-12
-8
-4
0
4
8
12

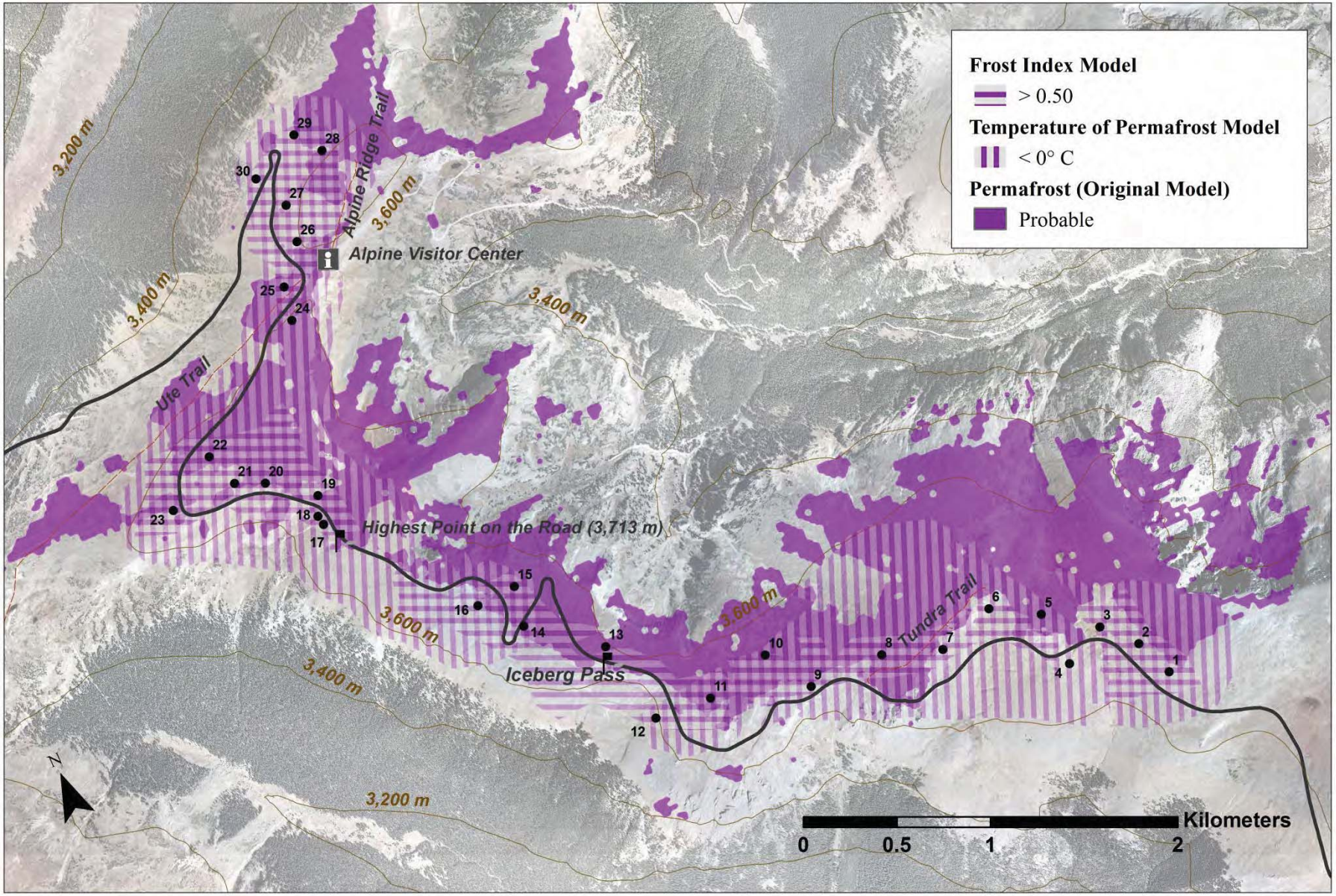


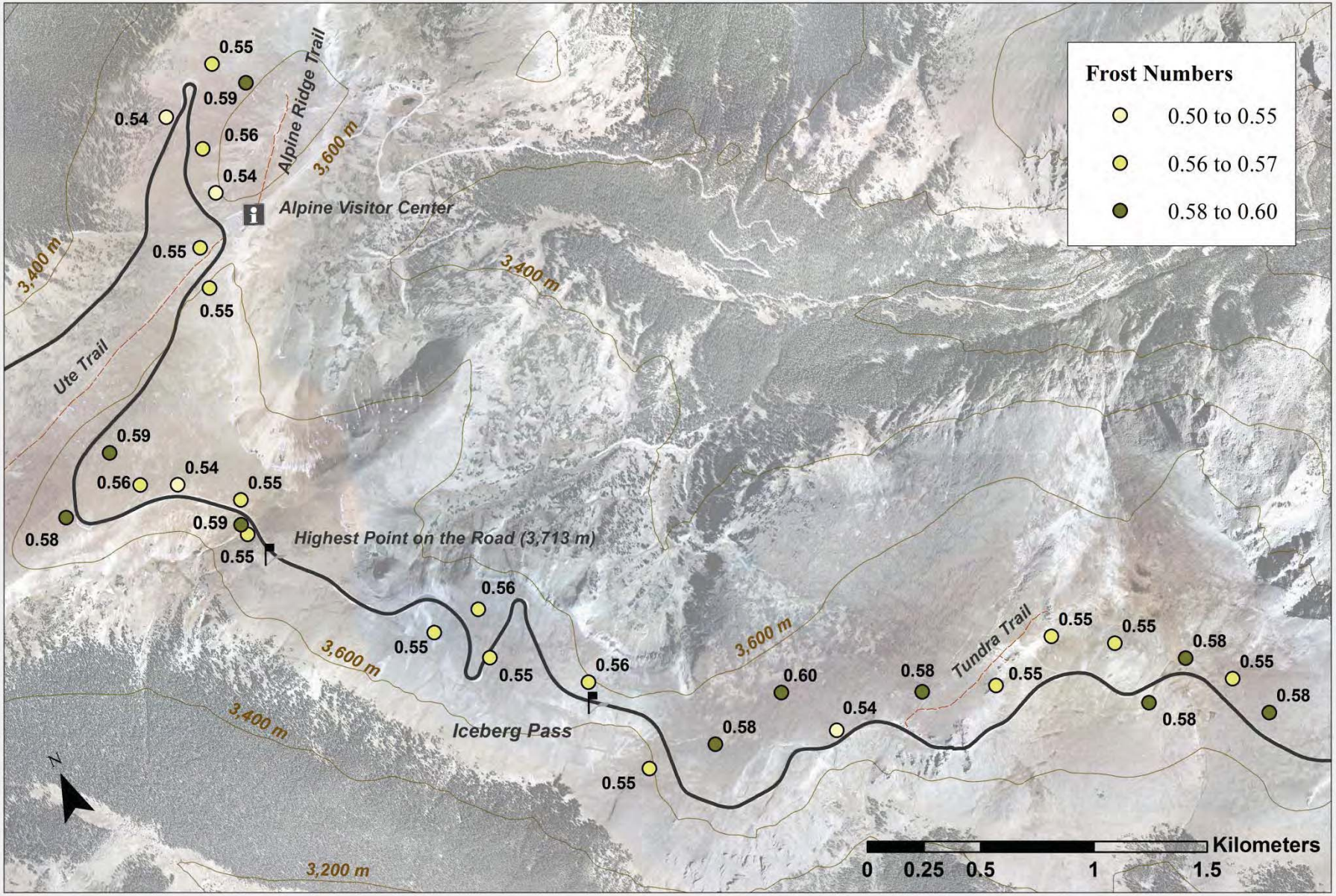
	July	August	September	October	November	December	January	February	March	April	May	June
0	10.5	10.7	10.7	3.0	-4.3	-5.0	-7.4	-8.1	-5.9	-4.2	-2.8	2.2
-1	6.9	9.0	9.0	5.7	1.0	-1.2	-3.3	-4.8	-4.2	-3.4	-2.4	-0.5
-2	3.0	6.3	6.3	6.4	3.0	1.0	-0.2	-1.9	-2.5	-2.3	-1.9	-0.7
-3	1.0	4.2	4.2	6.0	3.7	1.9	0.8	-0.2	-1.1	-1.4	-1.3	-0.7
-4	0.0	2.1	2.1	5.0	4.0	2.5	1.5	0.7	0.0	-0.4	-0.6	-0.5
-5	-0.1	0.9	0.9	4.1	3.7	2.7	1.7	1.0	0.4	0.0	-0.2	-0.2
-6	-0.1	0.2	0.2	3.0	3.2	2.6	2.0	1.4	0.8	0.4	0.2	0.1

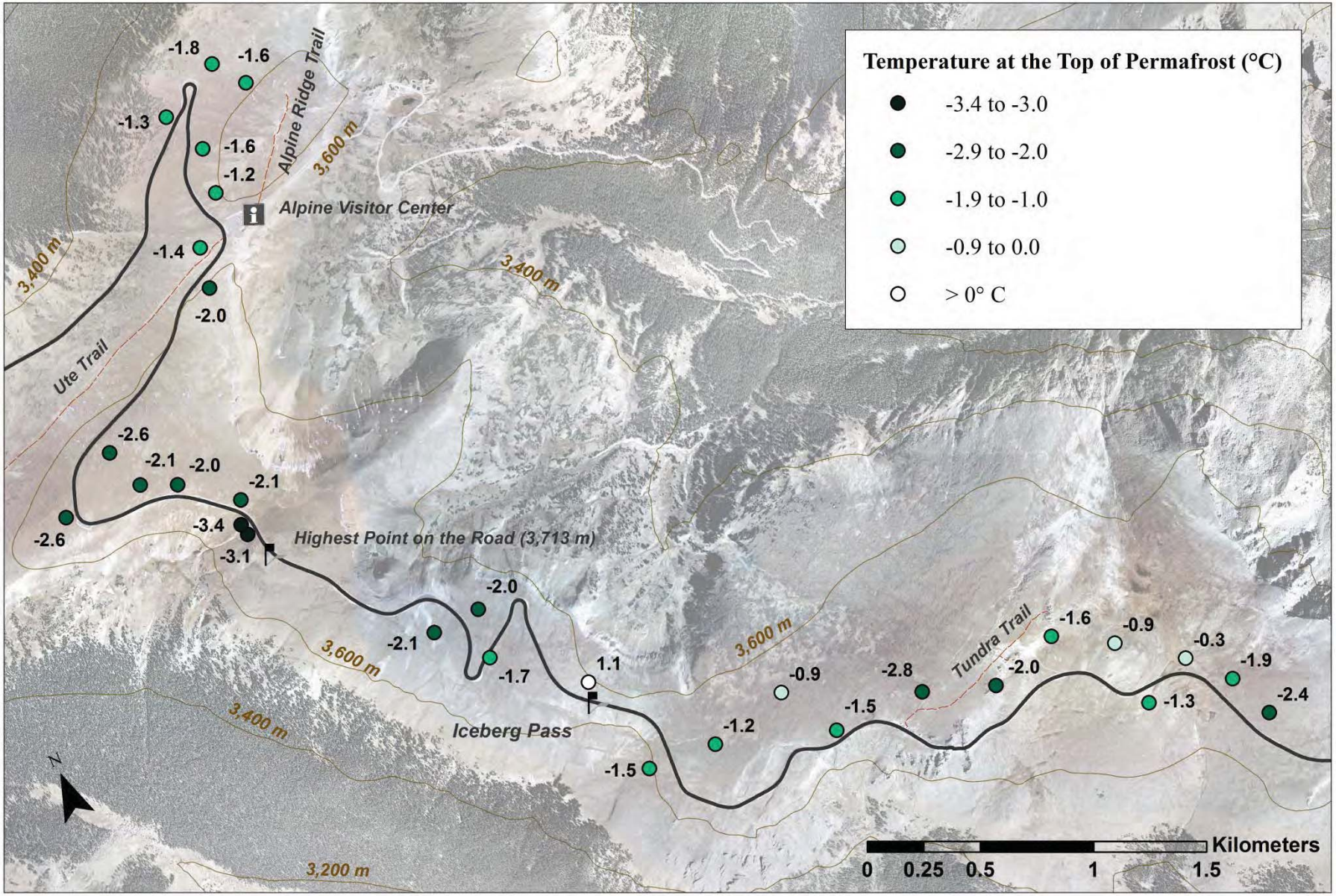

Production of CO2 in Alpine Soils (ppm)
5000
4000
3000
2000
1000
0
6/10/2011
6/25/2011
7/10/2011
7/25/2011
Tundra (mineral)
Tundra (organic)
Forest



http://www.mscd.edu/~eas/Janke/GEL_3420/ROMO/Home.htm


Frost Index Model
> 0.50
Temperature of Permafrost Model
< 0° C
Permafrost (Original Model)
Probable
3,200 m
3,400 m
3,600 m
Alpine Ridge Trail
Alpine Visitor Center
Ute Trail
Highest Point on the Road (3,713 m)
Iceberg Pass
Tundra Trail
N
Kilometers
0
0.5
1
2


Frost Numbers
0.50 to 0.55
0.56 to 0.57
0.58 to 0.60
Alpine Ridge Trail
3,600 m
Alpine Visitor Center
3,400 m
Ute Trail
Highest Point on the Road (3,713 m)
Iceberg Pass
Tundra Trail
3,200 m
N
Kilometers
0 0.25 0.5 1 1.5


Temperature at the Top of Permafrost (°C)
-3.4 to -3.0
-2.9 to -2.0
-1.9 to -1.0
-0.9 to 0.0
> 0° C
Alpine Visitor Center
Alpine Ridge Trail
Ute Trail
Tundra Trail
Highest Point on the Road (3,713 m)
Iceberg Pass
3,200 m
3,400 m
3,600 m
N
Kilometers
0 0.25 0.5 1 1.5