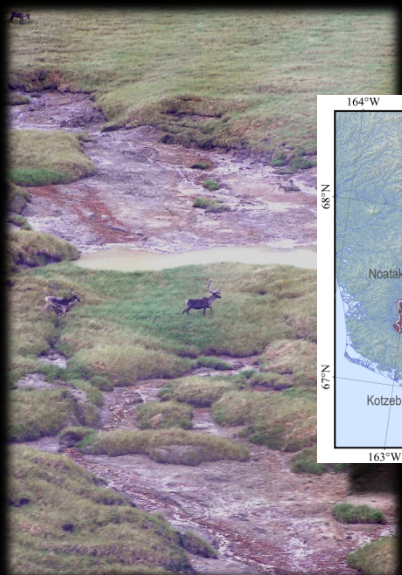
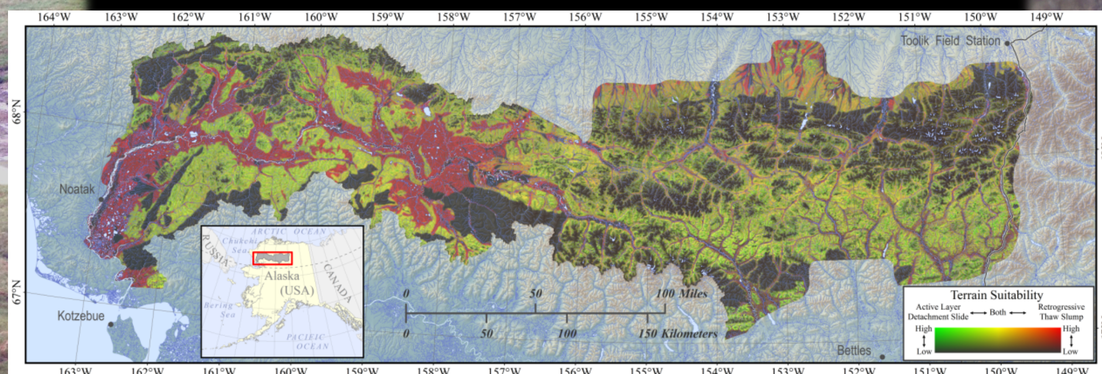
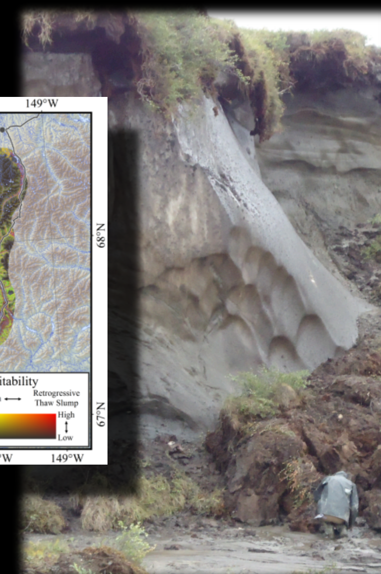
DRIVERS AND ESTIMATES OF TERRAIN SUITABILITY FOR ACTIVE LAYER DETACHMENT SLIDES AND RETROGRESSIVE THAW SLUMPSIN THE BROOKS RANGE AND FOOTHILLS OF NORTHWEST ALASKA, USA







Andrew W. Balser

Climate Change Science Inst., Oak Ridge National Laboratory

Permafrost

~ 25% of the global terrestrial surface

~1,700 Pg of soil carbon

twice the current atmospheric load

more than half the global soil carbon pool

Permafrost degradation → CO_2, CH_4, N_2O

Global warming potential (IPCC 2013)

$CO_2 = 1$, $CH_4 = 34$, $N_2O = 298$

Arctic Landscape Change Processes

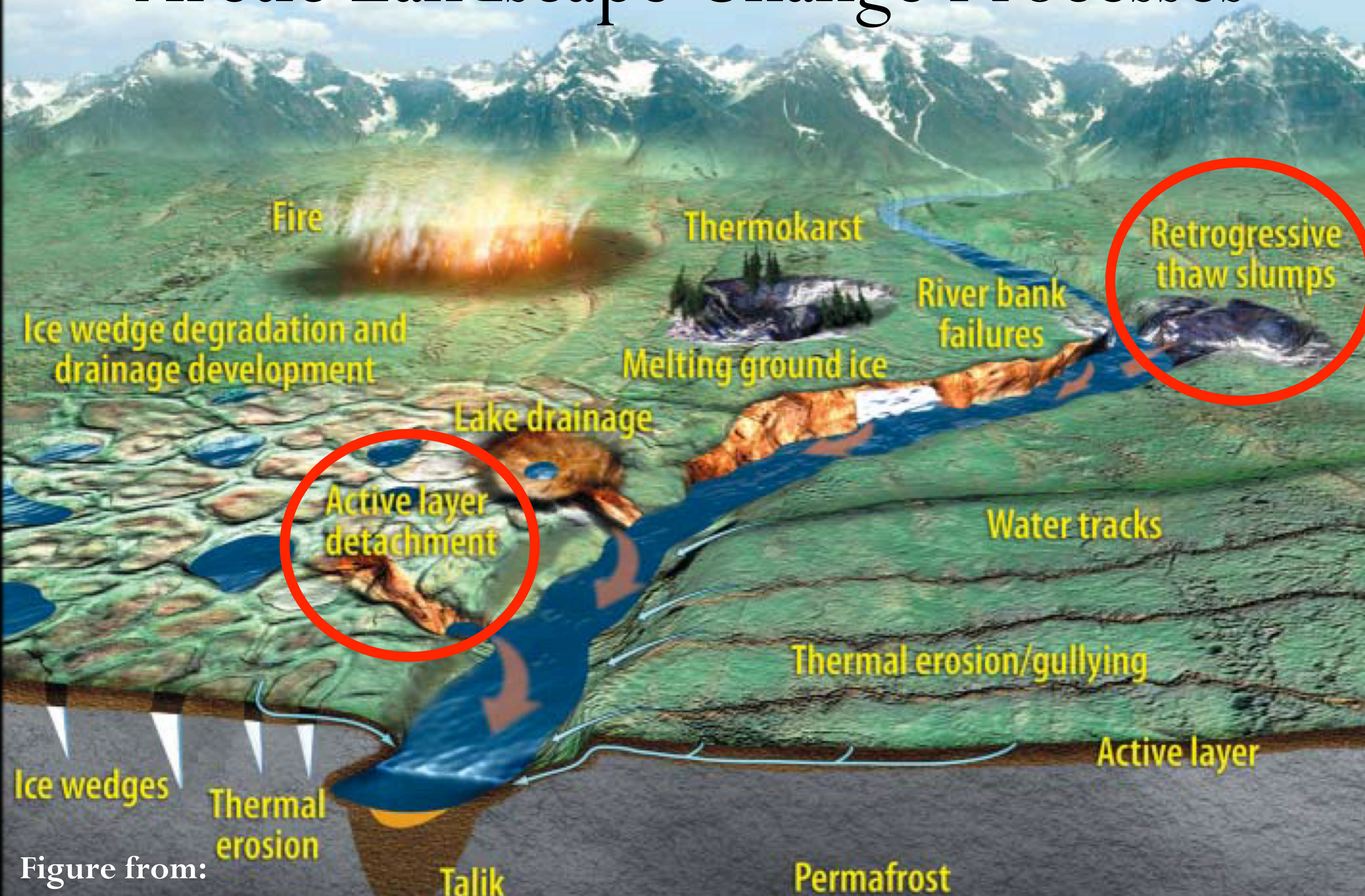
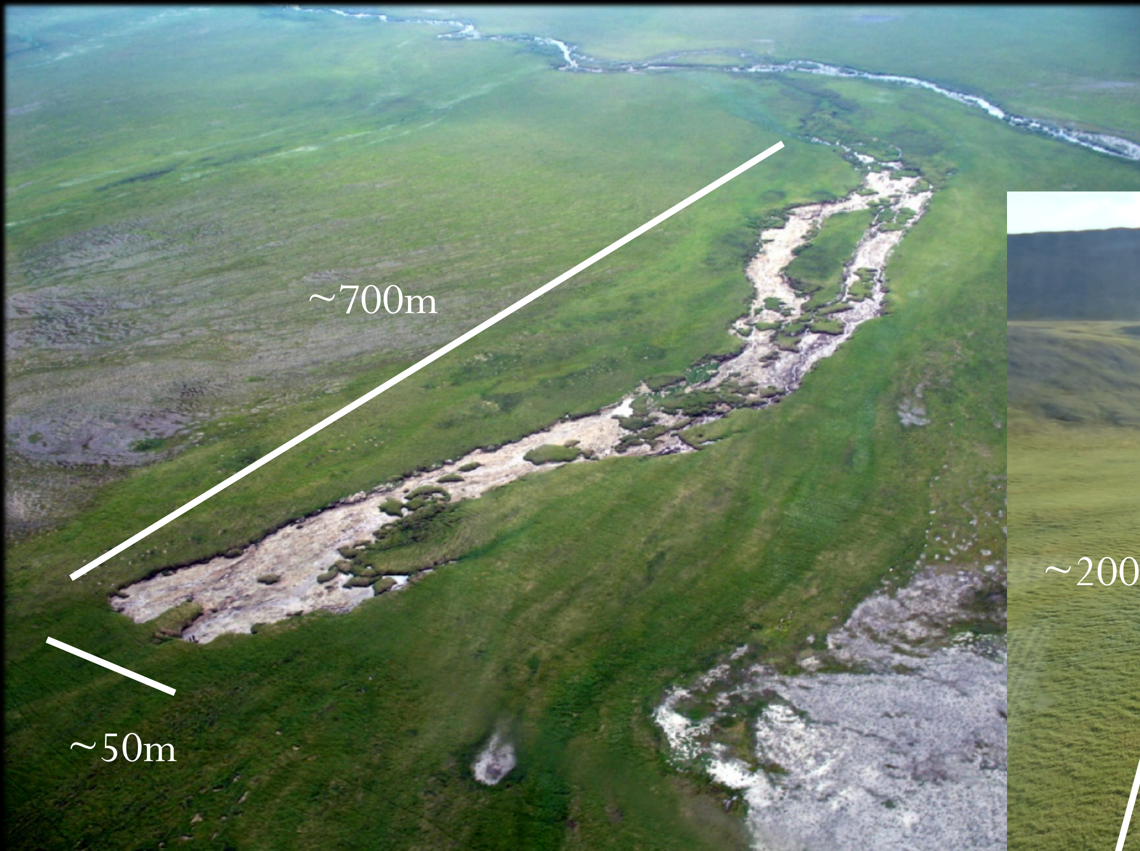
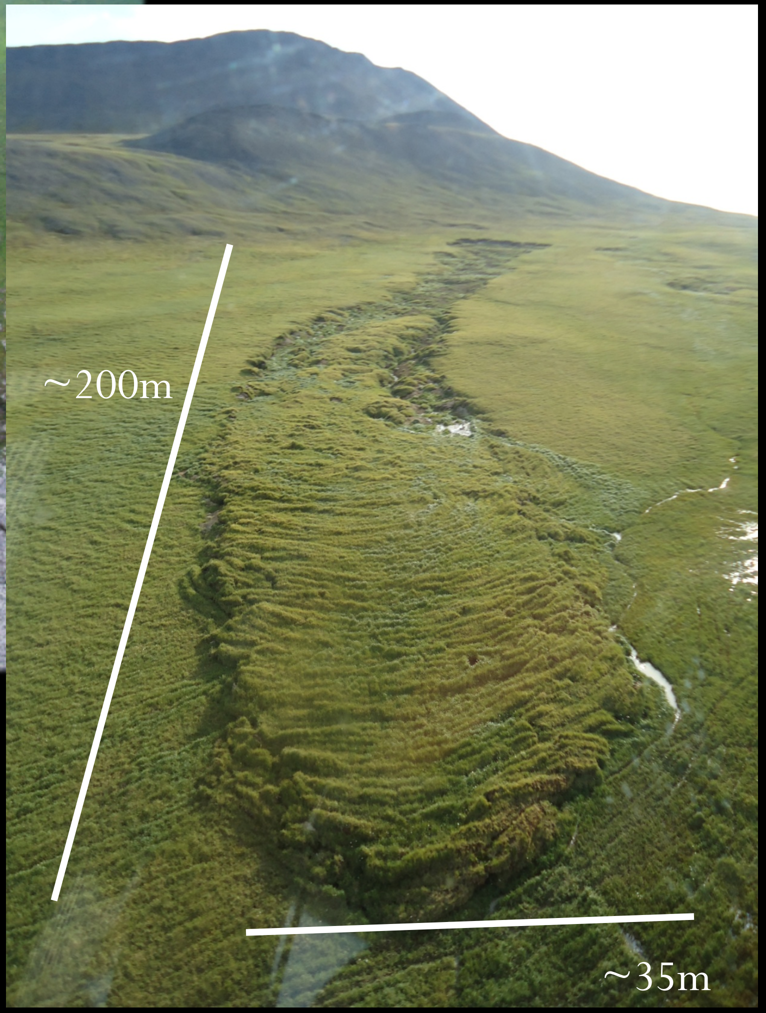


Figure from:
Rowland, J. C., et al. (2010), Arctic landscapes in transition - Geomorphic responses to degrading permafrost., *EOS*, *91*(26), 229-230.

Active Layer Detachment Slides (ALD)





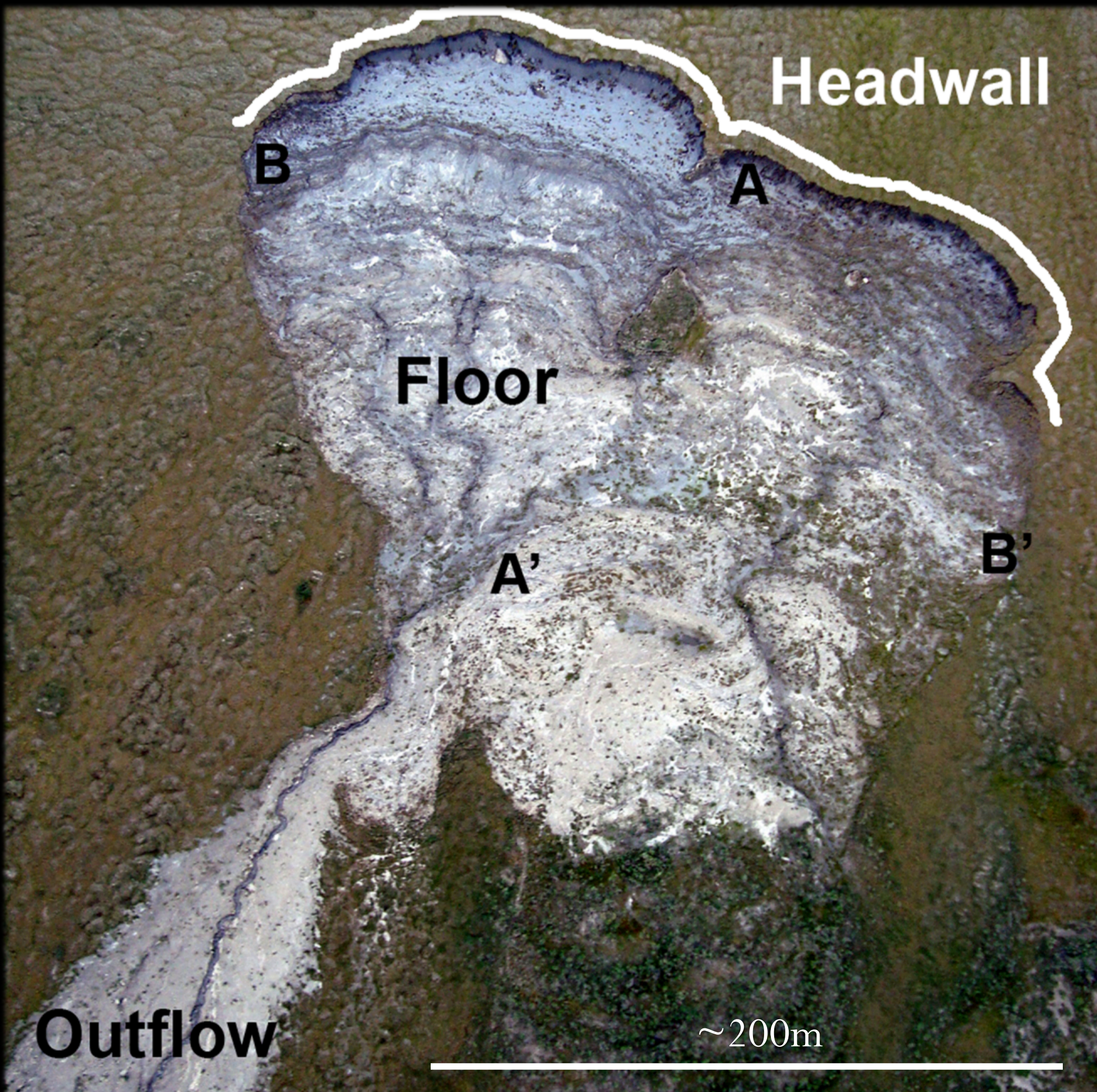
Pore pressure exceeds shear strength

Surficial – top 1 – 2m

Stabilize after 1-2 years (typically)

(photos: Noatak Basin, 2006)

Retrogressive Thaw Slumps (RTS)



Large & Deep

Depth ~ 14m

(@ headwall scarp)

A – A' = 181m

B – B' = 287m

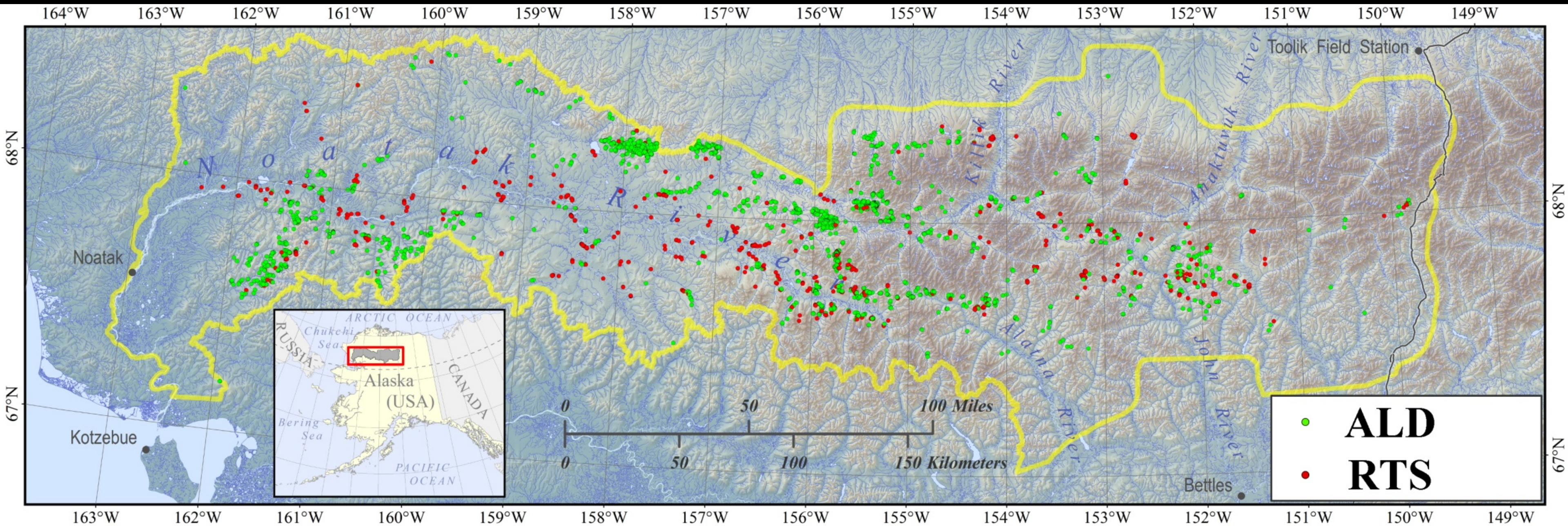
Years to Decades

Headwall Retreat

1 to 10+ m/yr

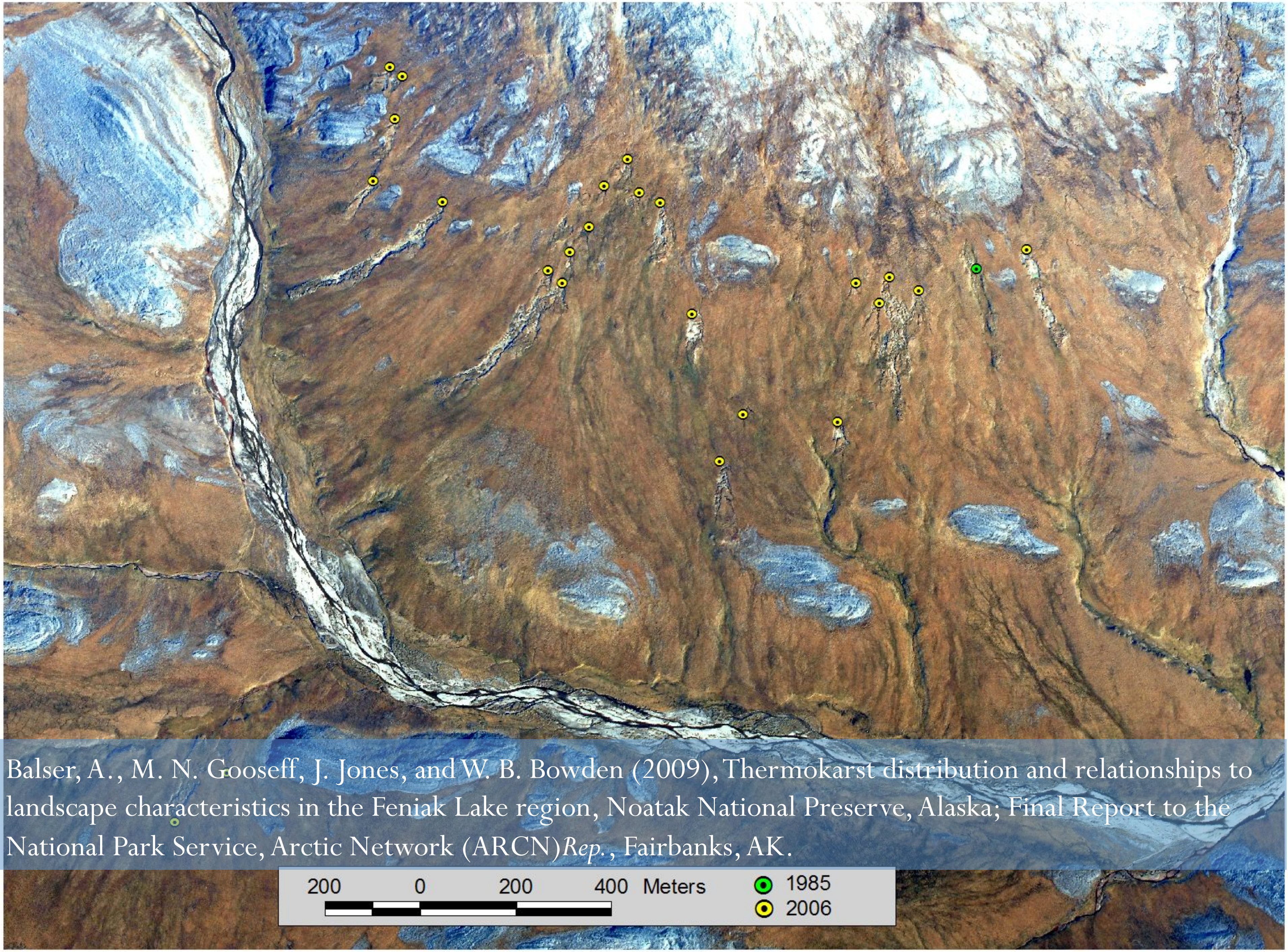
(photo: Noatak Basin, 2011)

ALD & RTS Features in the Central and Western Brooks Range and Foothills



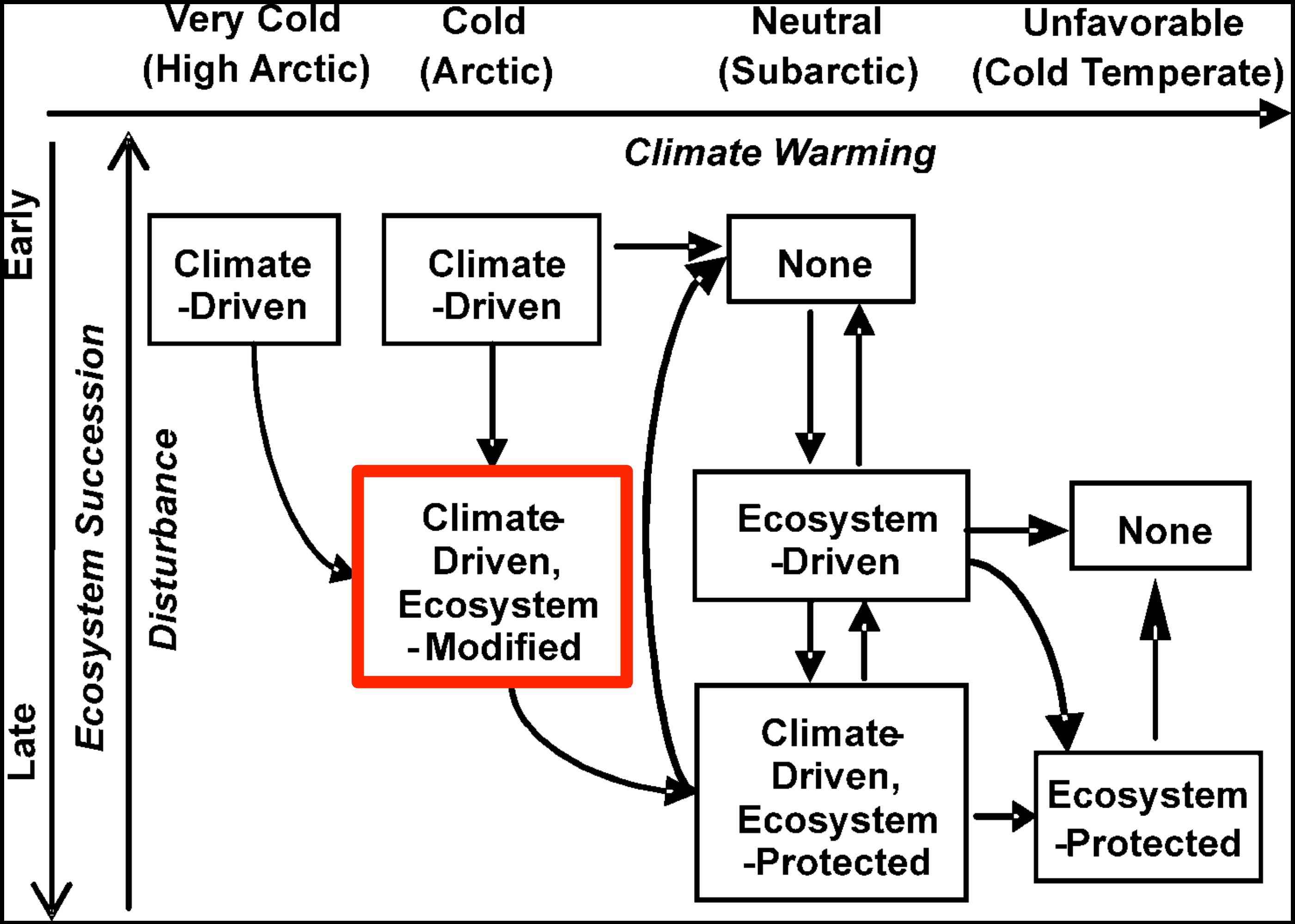
2,492 Active Layer Detachment Slides (ALD)

805 Retrogressive Thaw Slumps (RTS)



Balser, A., M. N. Gooseff, J. Jones, and W. B. Bowden (2009), Thermokarst distribution and relationships to landscape characteristics in the Feniak Lake region, Noatak National Preserve, Alaska; Final Report to the National Park Service, Arctic Network (ARCN) *Rep.*, Fairbanks, AK.

Permafrost in Relation to Climate and Ecosystems

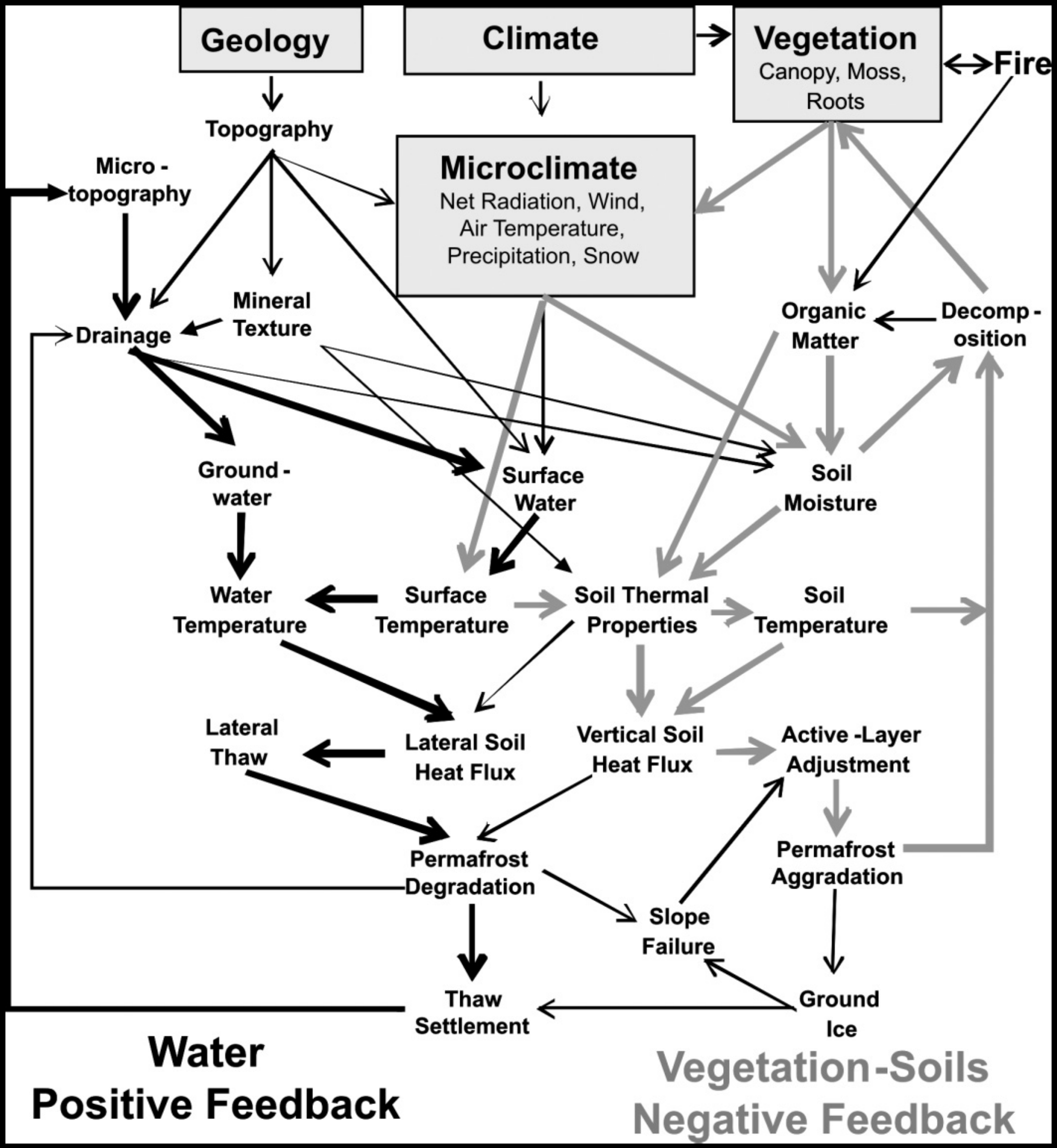


Shur, Y. L., and M. T. Jorgenson (2007), Patterns of Permafrost Formation and Degradation in Relation to Climate and Ecosystems, *Permafrost and Periglacial Processes*, *18*, 7 - 19.

Conceptual Model:

Factor interactions and feedbacks affecting permafrost with climate change.

Apply at a regional scale



Jorgenson, M. T., V. Romanovsky, J. Harden, Y. Shur, J. O'Donnell, E. A. G. Schuur, M. Kanevskiy, and S. Marchenko (2010), Resilience and vulnerability of permafrost to climate change, *Can J Forest Res*, *40*(7), 1219-1236, doi:10.1139/x10-060.

‘Permafrost’ includes vast diversity

Properties: from complex interactions

Where might features occur?

How much terrain is that?

Terrain Suitability Estimates

Categorical factors

Integrated Terrain Unit (ITU) analysis

- Lithology
- Surficial Geology
- Ecotype

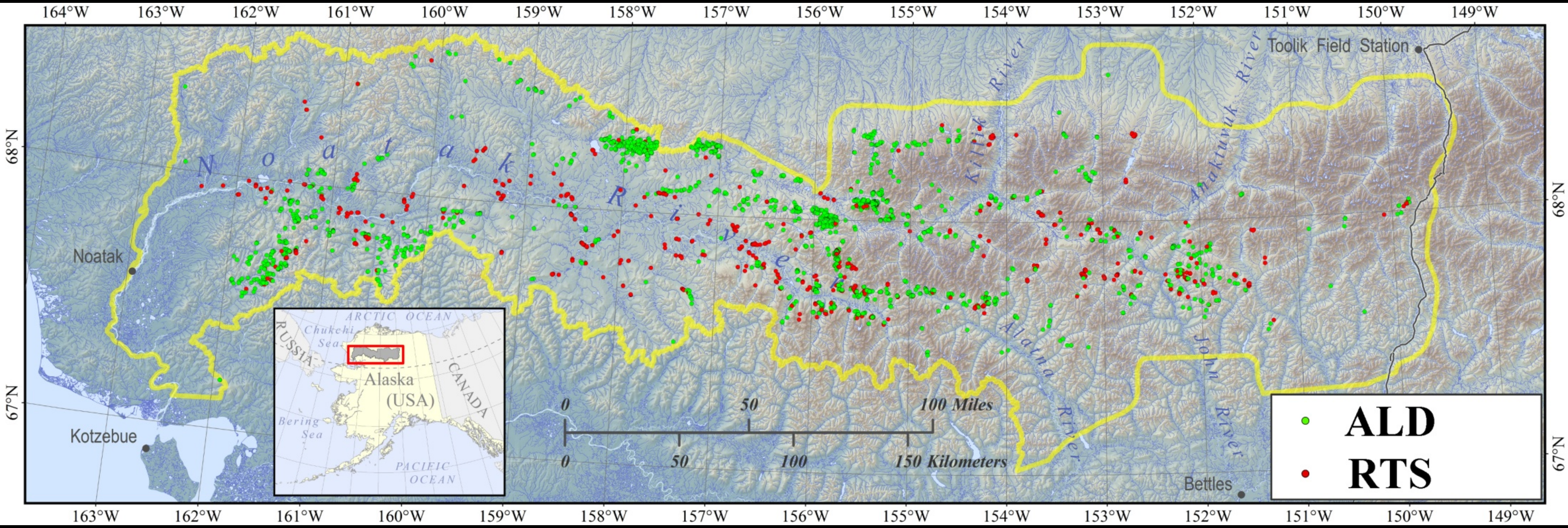
Continuous factors

Structural Equation Modelling (SEM) analysis

- Vegetation
- Topography
- Geomorphology

Combine ITU & SEM results for final map

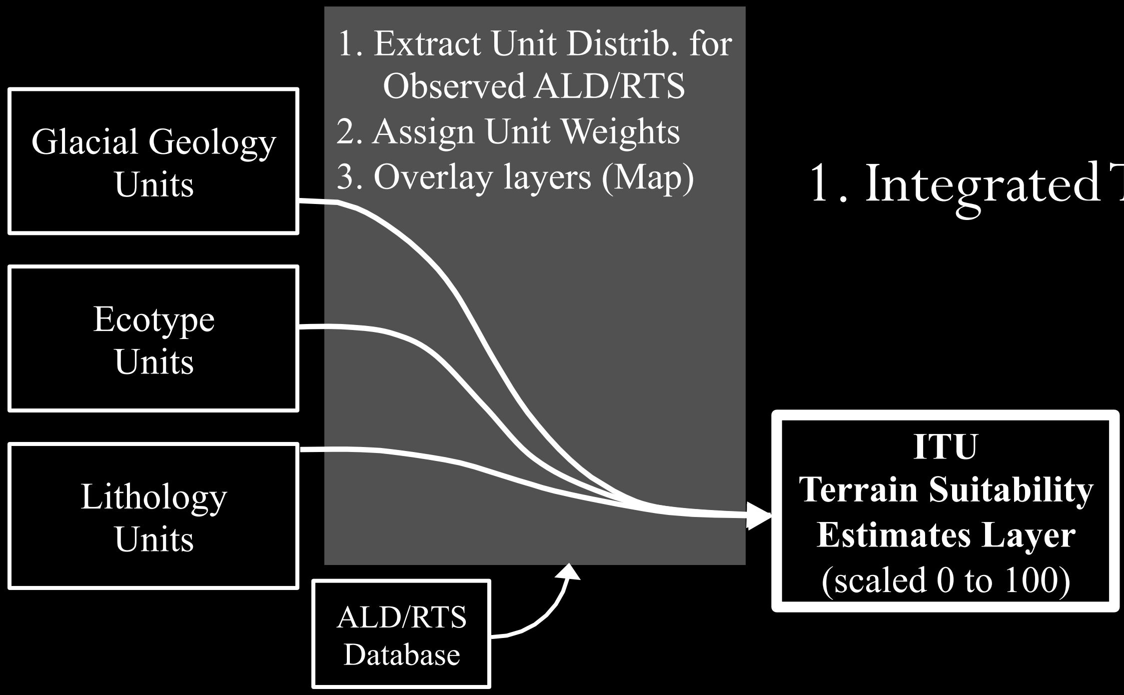
ALD & RTS Features in the Central and Western Brooks Range and Foothills



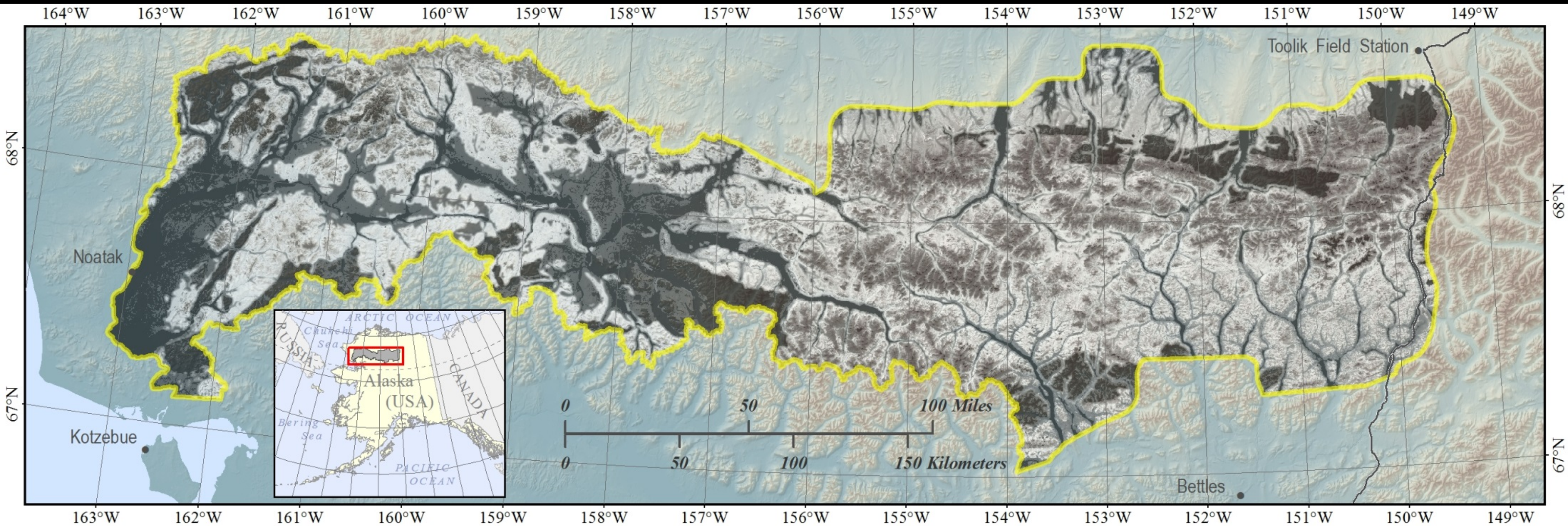
2,492 Active Layer Detachment Slides (ALD)

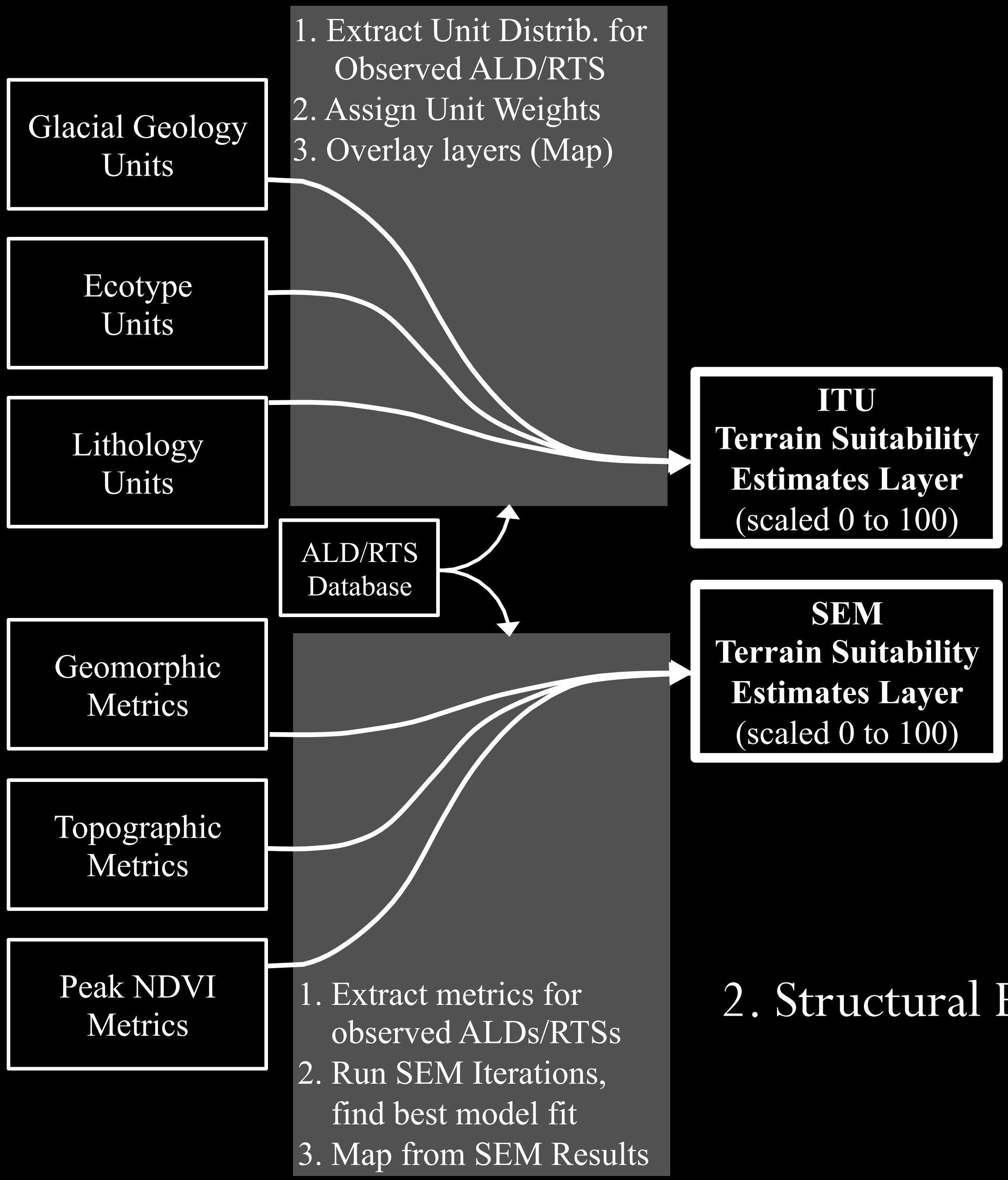
805 Retrogressive Thaw Slumps (RTS)

1. Integrated Terrain Unit (ITU) Analysis

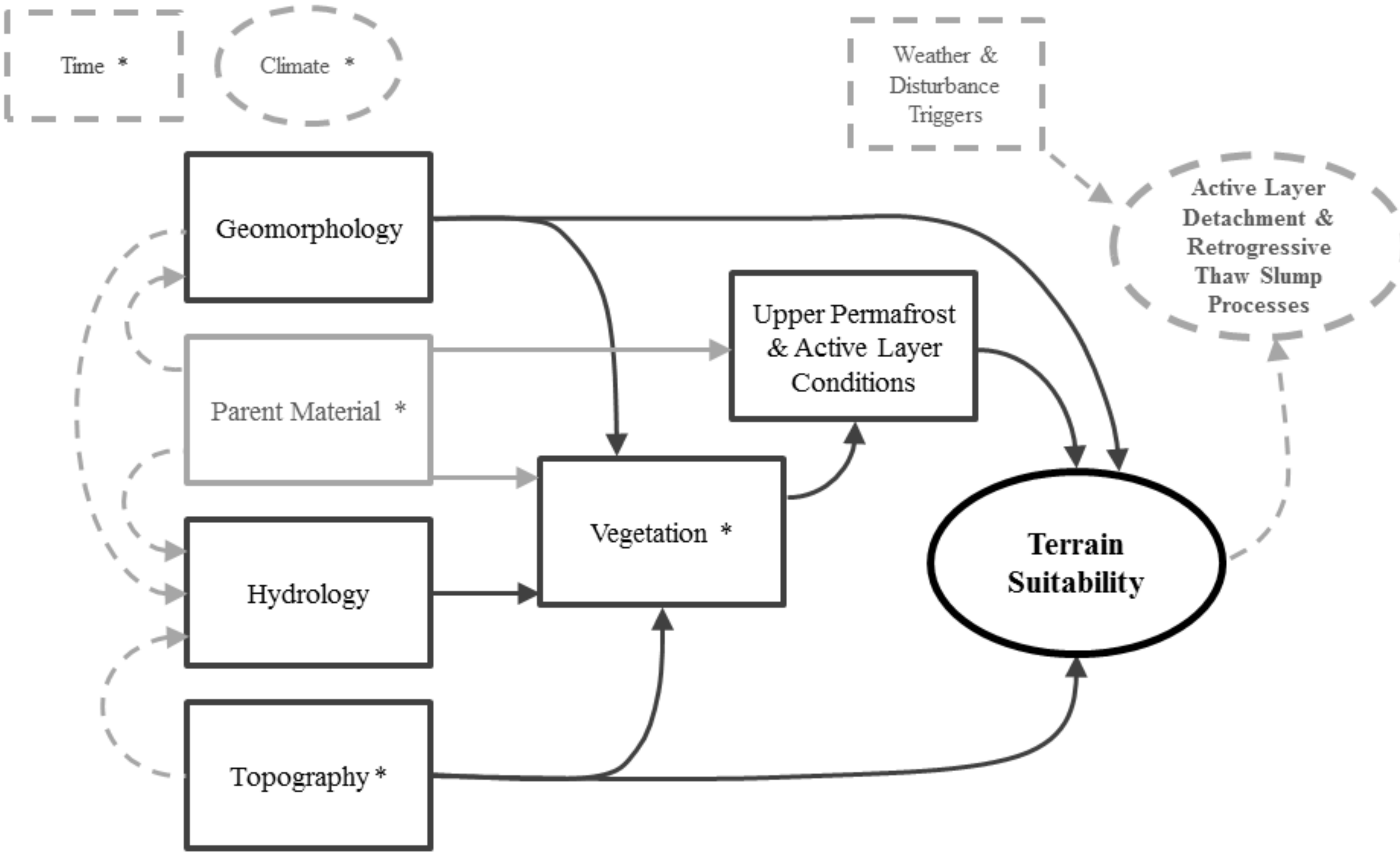


ITU results for ALD features

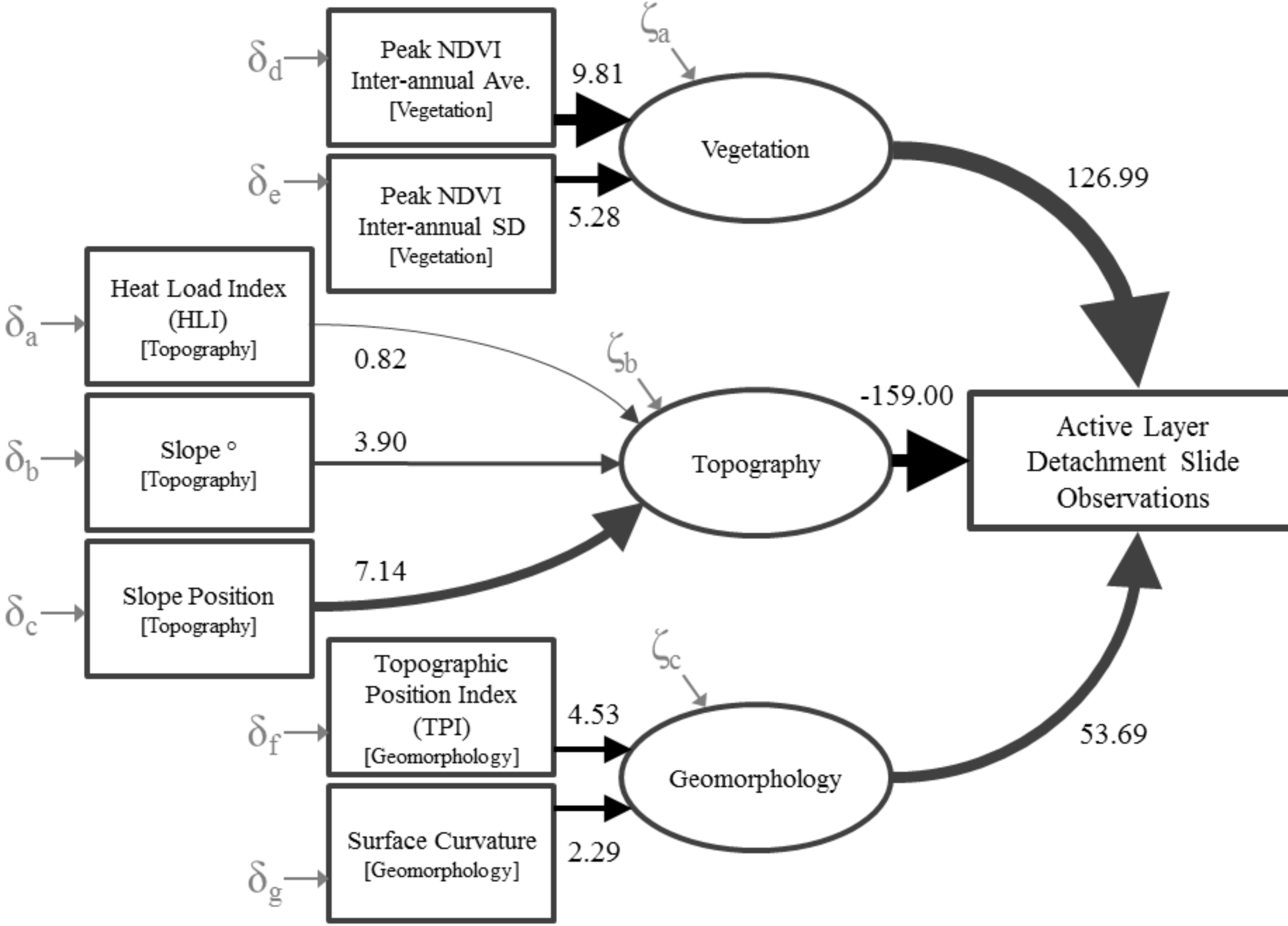




2. Structural Equation Modelling (SEM)

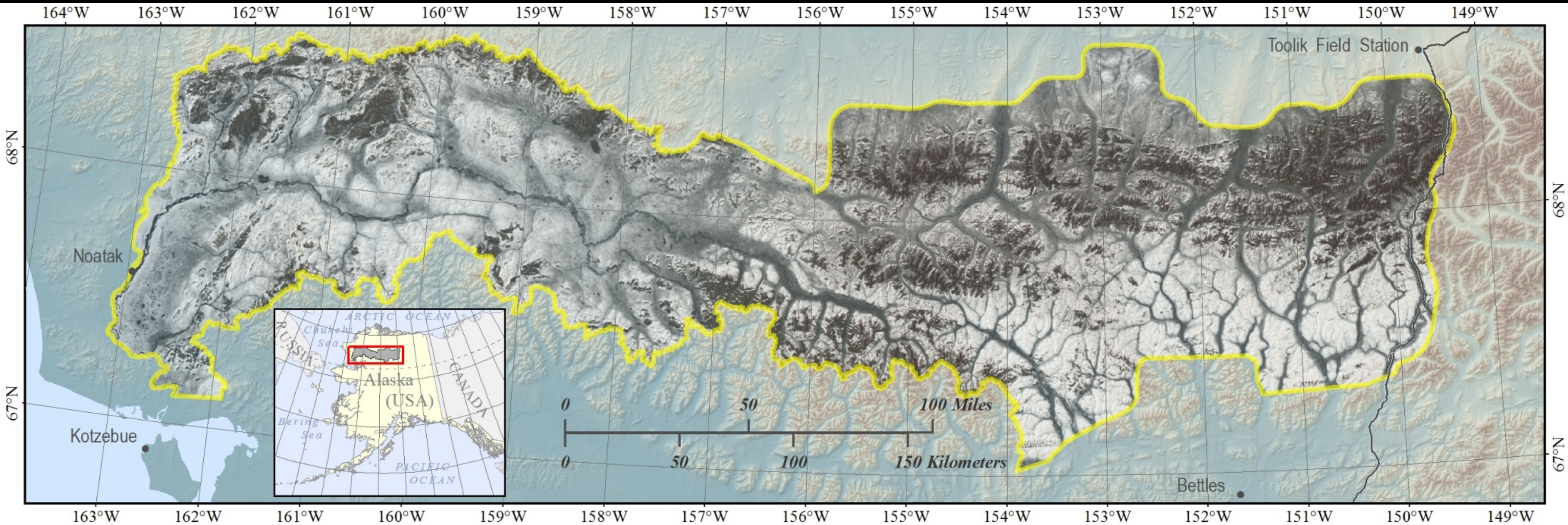


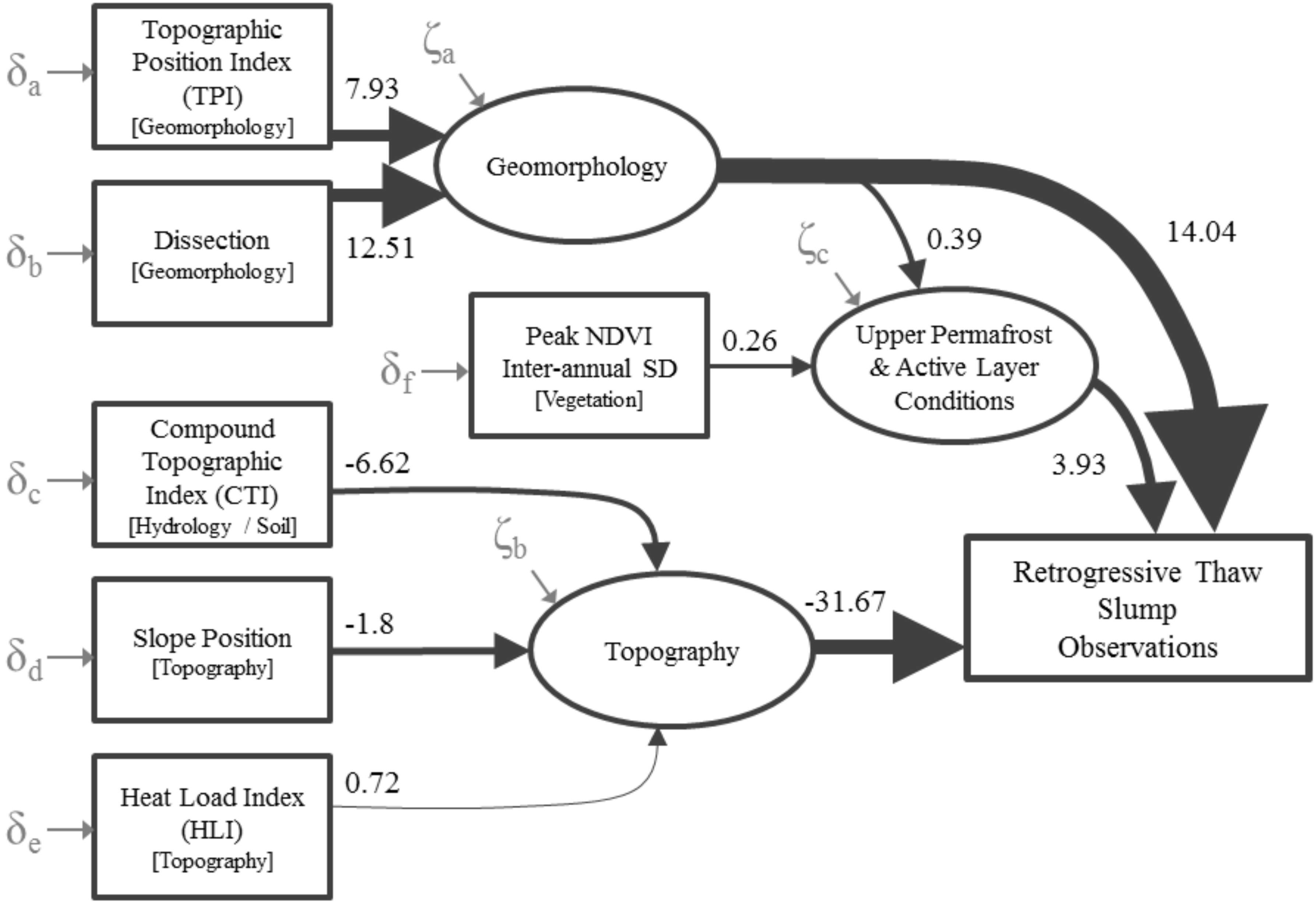
* State Factor. Jenny (1941); van Cleve et al. (1991)



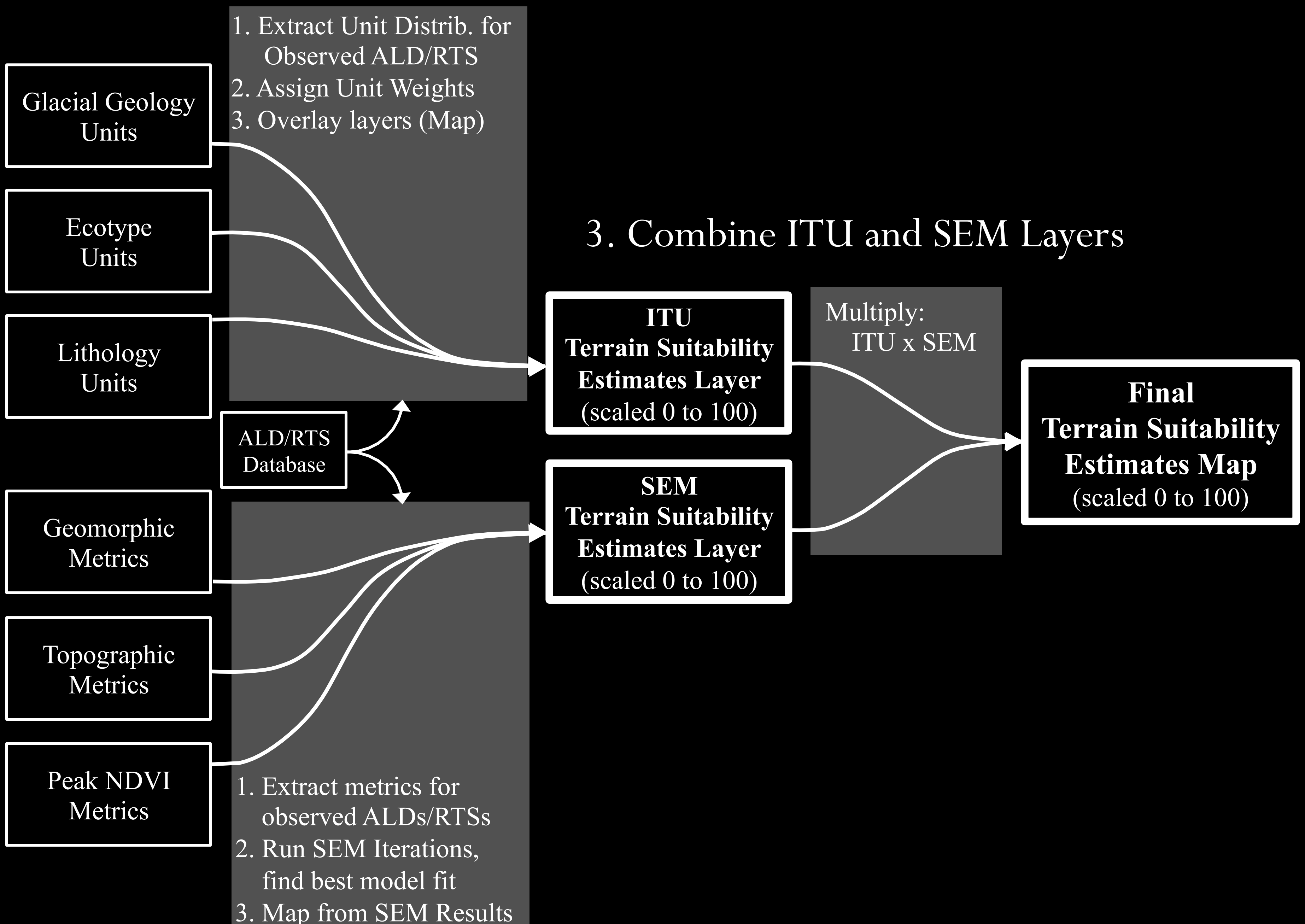
δd
Peak NDVI Inter-annual Ave. [Vegetation]
δe
Peak NDVI Inter-annual SD [Vegetation]
δa
Heat Load Index (HLI) [Topography]
δb
Slope ° [Topography]
δc
Slope Position [Topography]
δf
Topographic Position Index (TPI) [Geomorphology]
δg
Surface Curvature [Geomorphology]
ζa
ζb
ζc
9.81
5.28
0.82
3.90
7.14
4.53
2.29
Vegetation
Topography
Geomorphology
126.99
-159.00
53.69
Active Layer Detachment Slide Observations

SEM results for ALD features

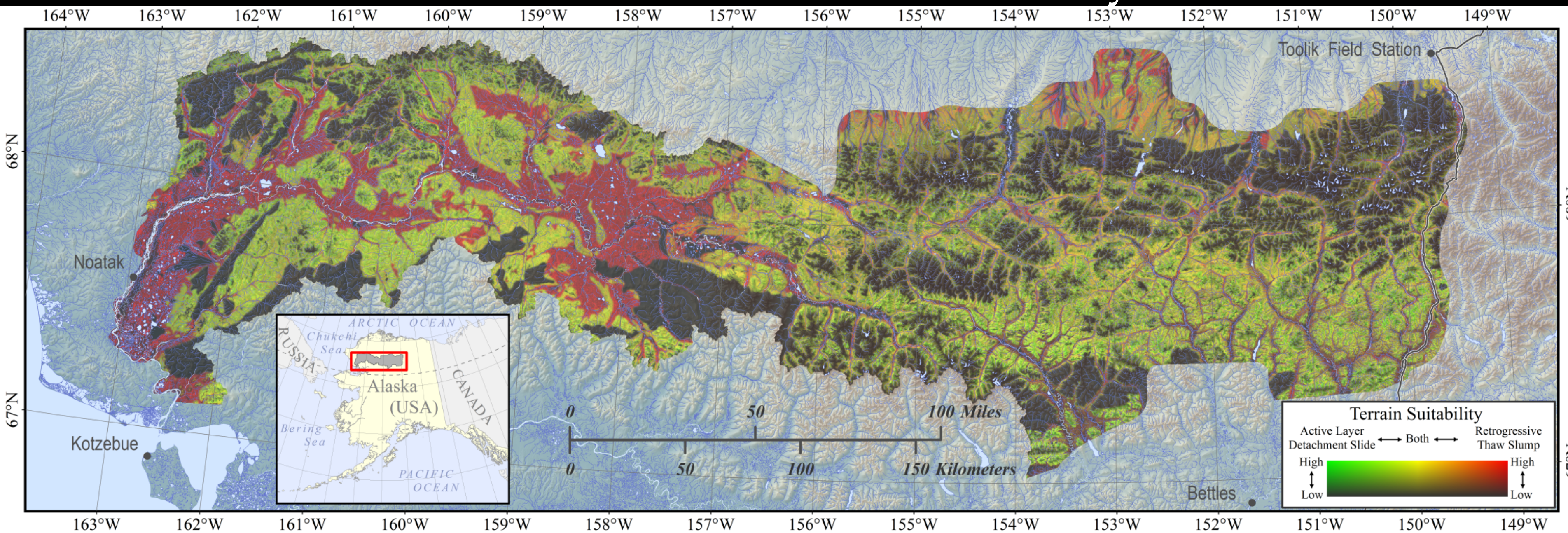


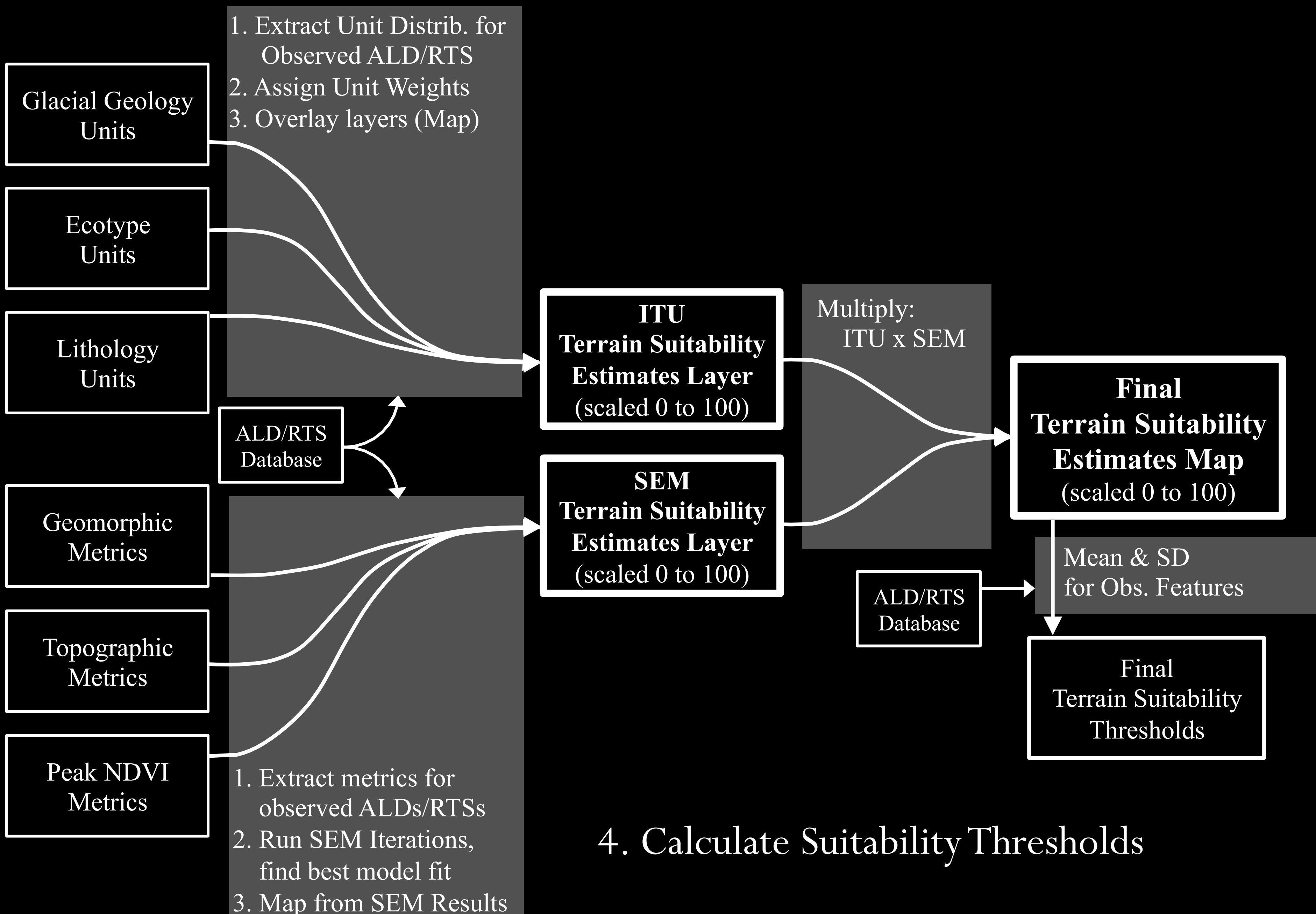


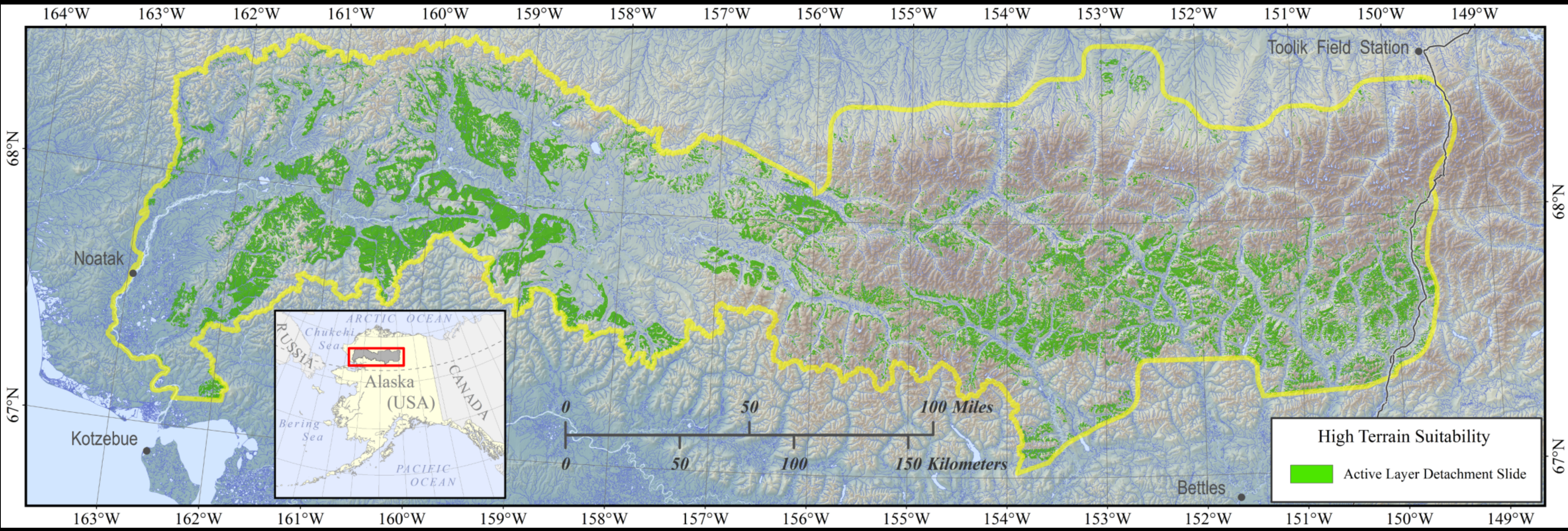
δa
δb
δc
δd
δe
δf
ζa
ζb
ζc
Topographic Position Index (TPI) [Geomorphology]
Dissection [Geomorphology]
Peak NDVI Inter-annual SD [Vegetation]
Compound Topographic Index (CTI) [Hydrology / Soil]
Slope Position [Topography]
Heat Load Index (HLI) [Topography]
Geomorphology
Upper Permafrost & Active Layer Conditions
Topography
Retrogressive Thaw Slump Observations
7.93
12.51
0.39
14.04
0.26
3.93
-6.62
-1.8
0.72
-31.67

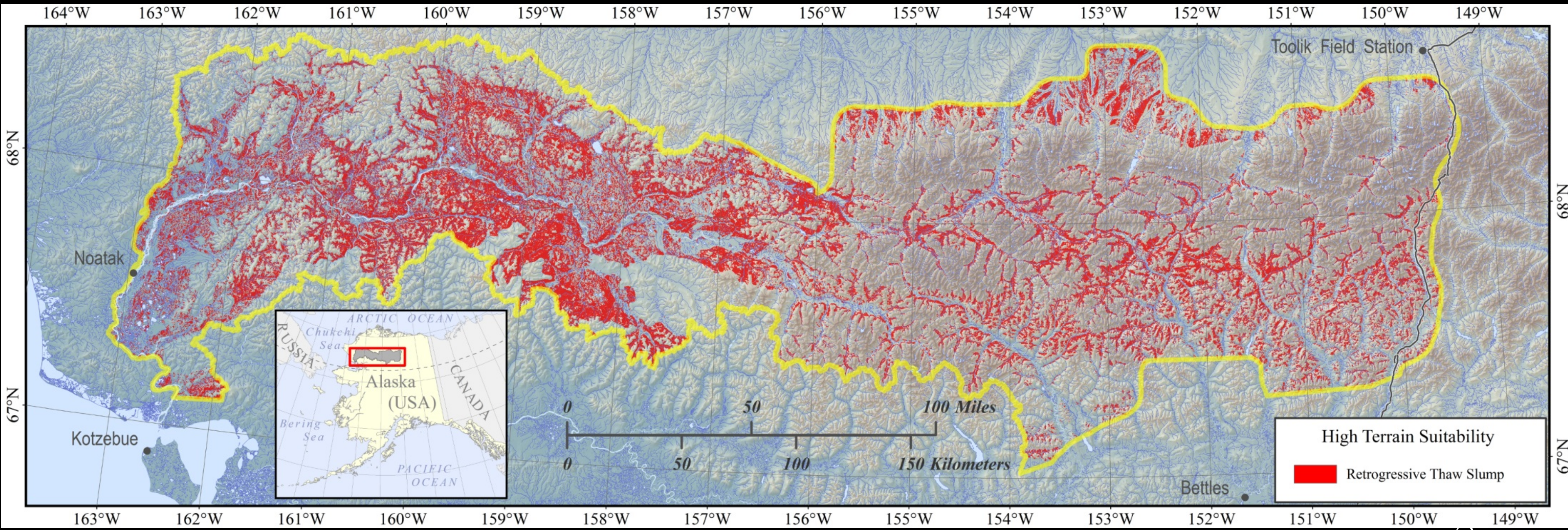

1. Extract Unit Distrib. for Observed ALD/RTS
2. Assign Unit Weights
3. Overlay layers (Map)
Glacial Geology Units
Ecotype Units
Lithology Units
3. Combine ITU and SEM Layers
ITU Terrain Suitability Estimates Layer (scaled 0 to 100)
Multiply: ITU x SEM
Final Terrain Suitability Estimates Map (scaled 0 to 100)
ALD/RTS Database
SEM Terrain Suitability Estimates Layer (scaled 0 to 100)
Geomorphic Metrics
Topographic Metrics
Peak NDVI Metrics
1. Extract metrics for observed ALDs/RTSs
2. Run SEM Iterations, find best model fit
3. Map from SEM Results

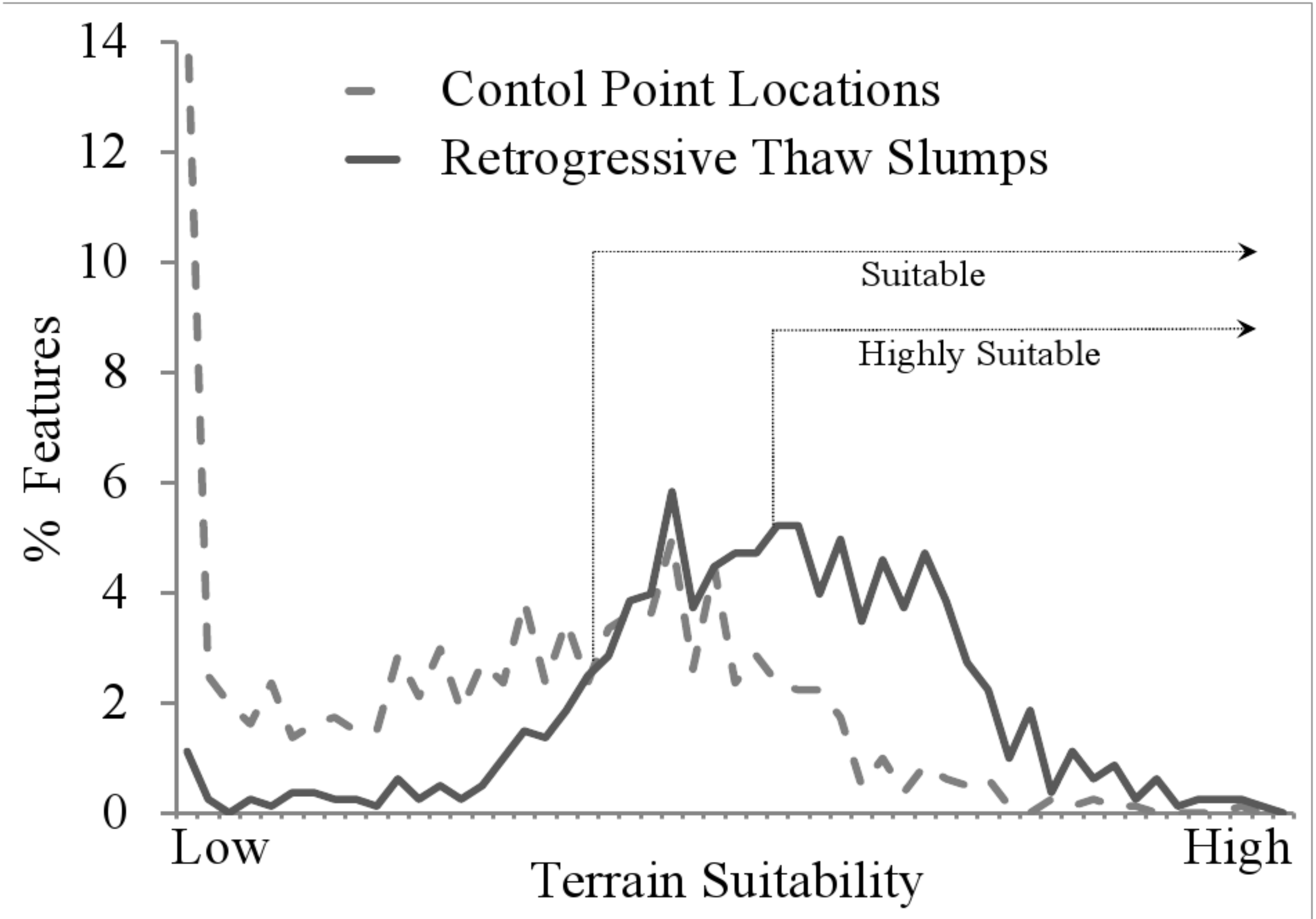
Final ALD and RTS Terrain Suitability Estimates



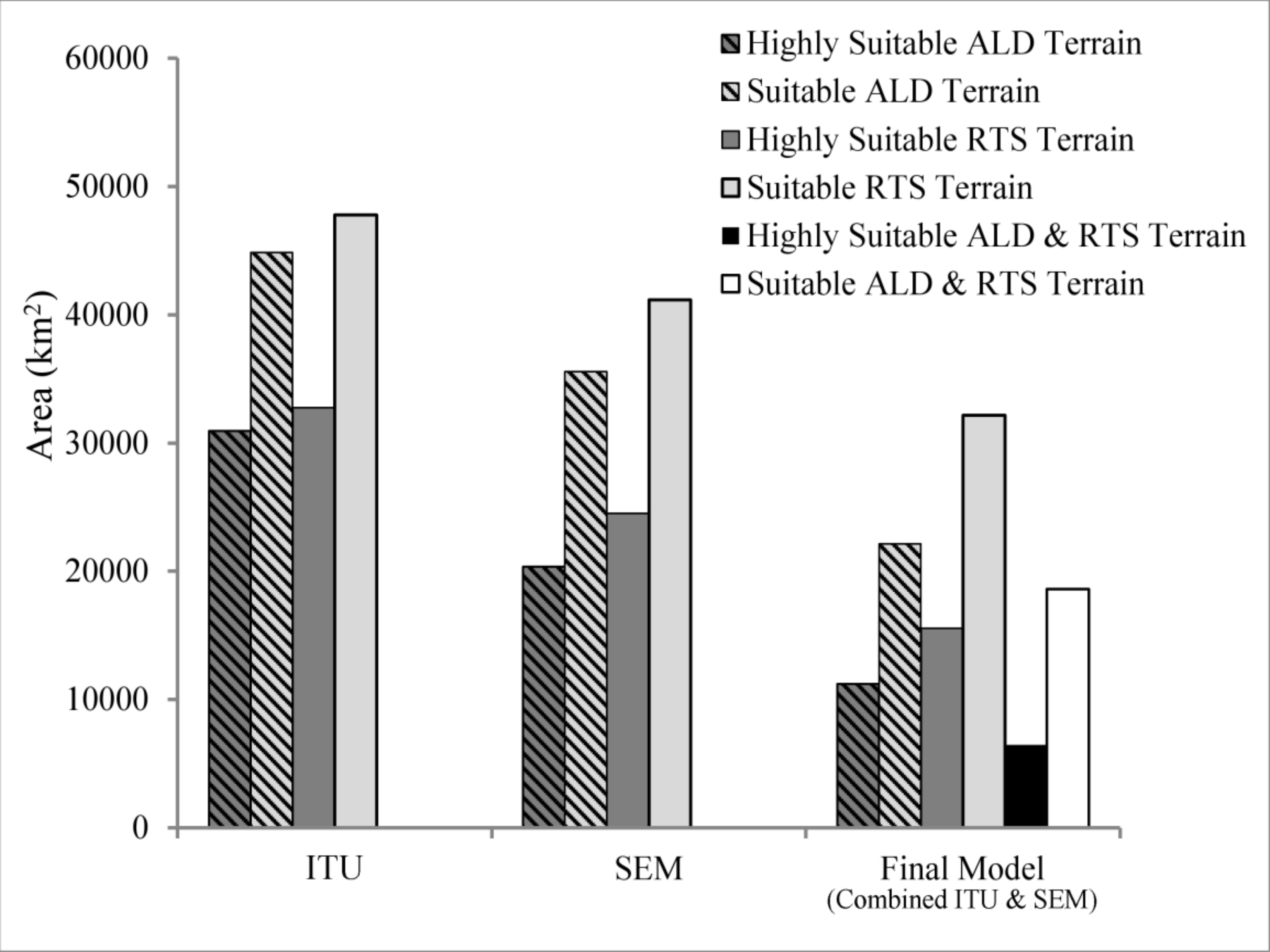

1. Extract Unit Distrib. for Observed ALD/RTS
2. Assign Unit Weights
3. Overlay layers (Map)
Glacial Geology Units
Ecotype Units
Lithology Units
ALD/RTS Database
Geomorphic Metrics
Topographic Metrics
Peak NDVI Metrics
1. Extract metrics for observed ALDs/RTSs
2. Run SEM Iterations, find best model fit
3. Map from SEM Results
ITU Terrain Suitability Estimates Layer (scaled 0 to 100)
SEM Terrain Suitability Estimates Layer (scaled 0 to 100)
Multiply: ITU x SEM
Final Terrain Suitability Estimates Map (scaled 0 to 100)
Mean & SD for Obs. Features
ALD/RTS Database
Final Terrain Suitability Thresholds
4. Calculate Suitability Thresholds


Toolik Field Station
Noatak
Kotzebue
Bettles
ARCTIC OCEAN
Chukchi Sea
RUSSIA
Alaska (USA)
CANADA
Bering Sea
PACIFIC OCEAN
0 50 100 Miles
0 50 100 150 Kilometers
High Terrain Suitability
Active Layer Detachment Slide
164°W 163°W 162°W 161°W 160°W 159°W 158°W 157°W 156°W 155°W 154°W 153°W 152°W 151°W 150°W 149°W
68°N
67°N

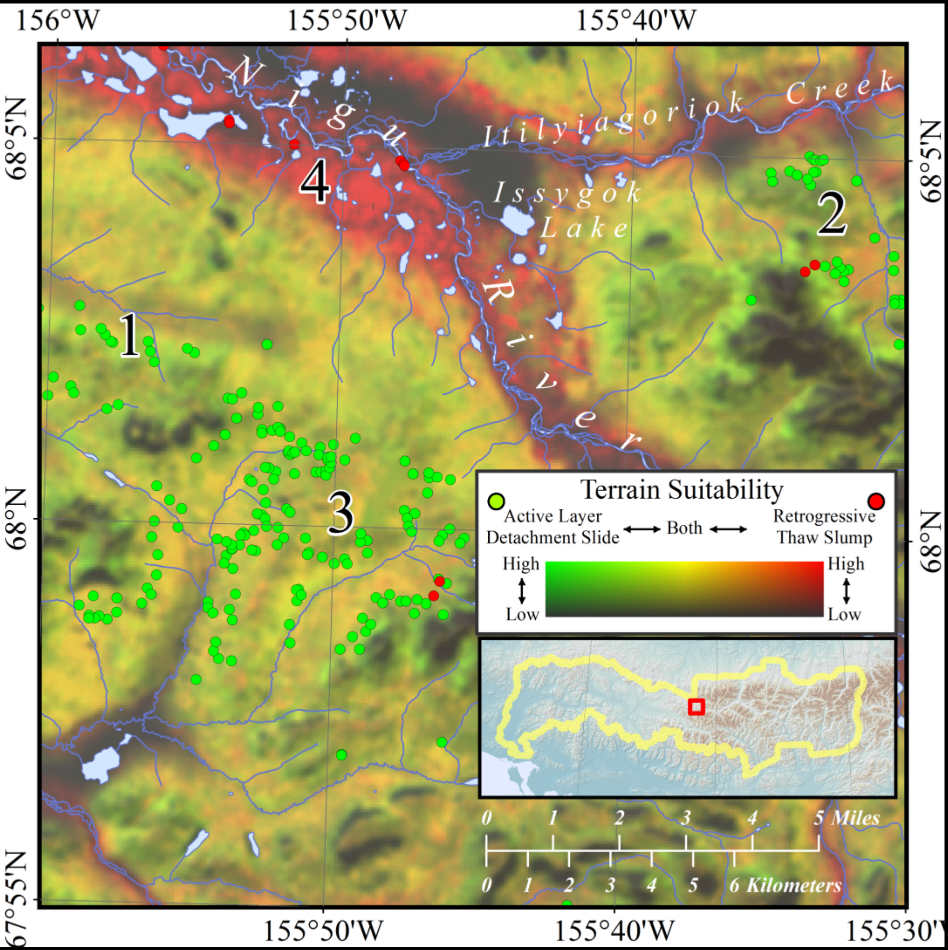

Toolik Field Station
Noatak
Kotzebue
Bettles
ARCTIC OCEAN
Chukchi Sea
RUSSIA
Alaska (USA)
CANADA
Bering Sea
PACIFIC OCEAN
0 50 100 Miles
0 50 100 150 Kilometers
High Terrain Suitability
Retrogressive Thaw Slump
164°W 163°W 162°W 161°W 160°W 159°W 158°W 157°W 156°W 155°W 154°W 153°W 152°W 151°W 150°W 149°W
68°N
67°N



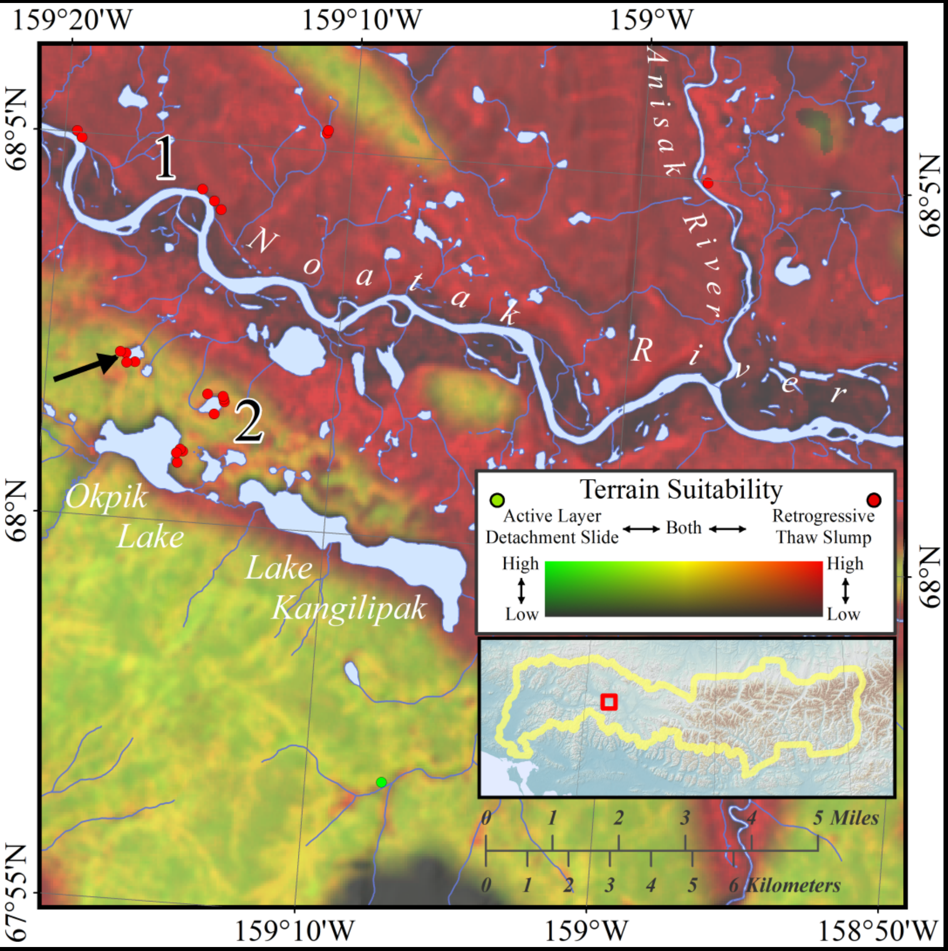
14
12
10
8
6
4
2
0
% Features
Contol Point Locations
Retrogressive Thaw Slumps
Suitable
Highly Suitable
Low
High
Terrain Suitability



Highly Suitable ALD Terrain
Suitable ALD Terrain
Highly Suitable RTS Terrain
Suitable RTS Terrain
Highly Suitable ALD & RTS Terrain
Suitable ALD & RTS Terrain
Area (km²)
60000
50000
40000
30000
20000
10000
0
ITU
SEM
Final Model
(Combined ITU & SEM)


156°W
155°50'W
155°40'W
155°30'W
68°5'N
68°N
67°55'N
Nigu River
Itilyiagoriok Creek
Issygok Lake
1
2
3
4
Terrain Suitability
Active Layer Detachment Slide
Both
Retrogressive Thaw Slump
High
Low
High
Low
0 1 2 3 4 5 Miles
0 1 2 3 4 5 6 Kilometers


1
2
3


159°20'W
159°10'W
159°W
68°5'N
68°N
67°55'N
68°5'N
68°N
159°10'W
159°W
158°50'W
1
2
Noatak
River
Anisak River
Okpik Lake
Lake Kangilipak
Terrain Suitability
Active Layer Detachment Slide
Both
Retrogressive Thaw Slump
High
Low
High
Low
0 1 2 3 4 5 Miles
0 1 2 3 4 5 6 Kilometers


1
2
3
N

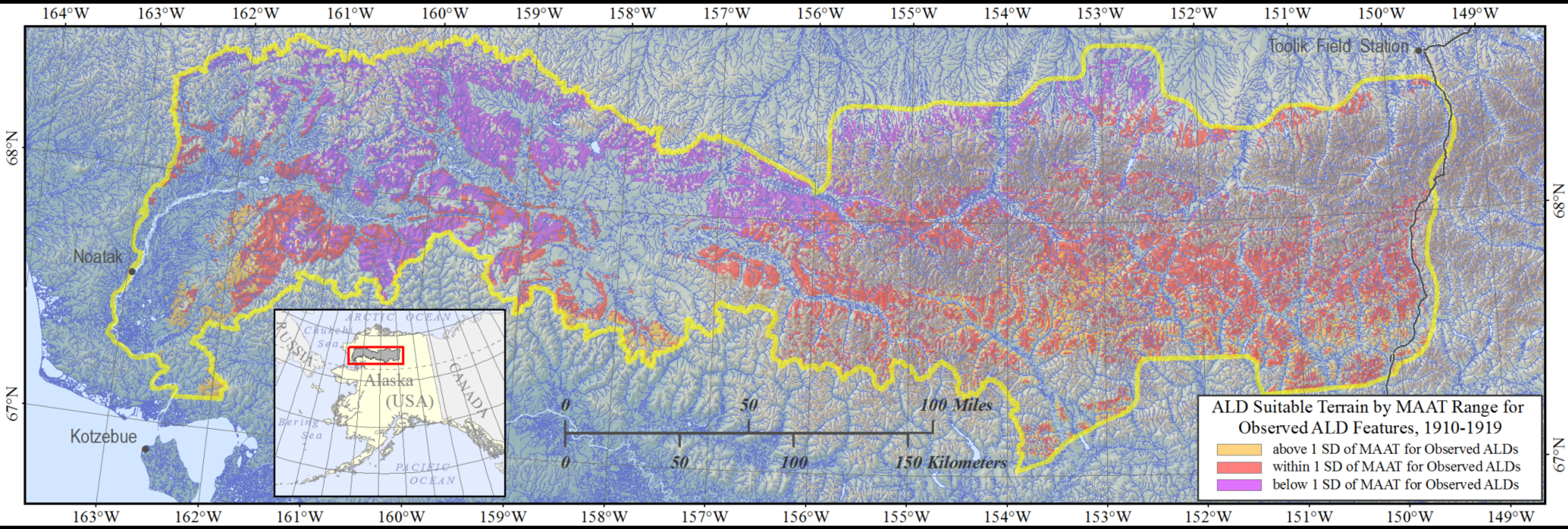
Summary

- Up to 57% of the study region is suitable terrain
- Suitable terrain is highly diverse
- Relevant factors constrain estimates
- Interactions drive suitability, further constrain estimates

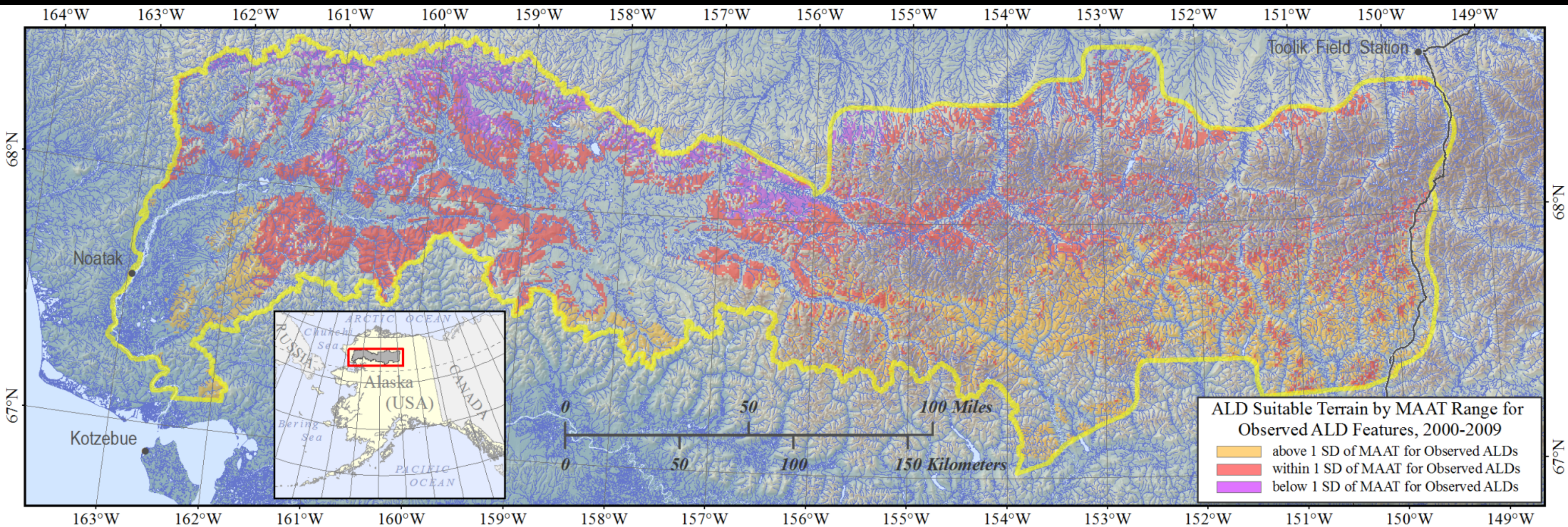
Take Home

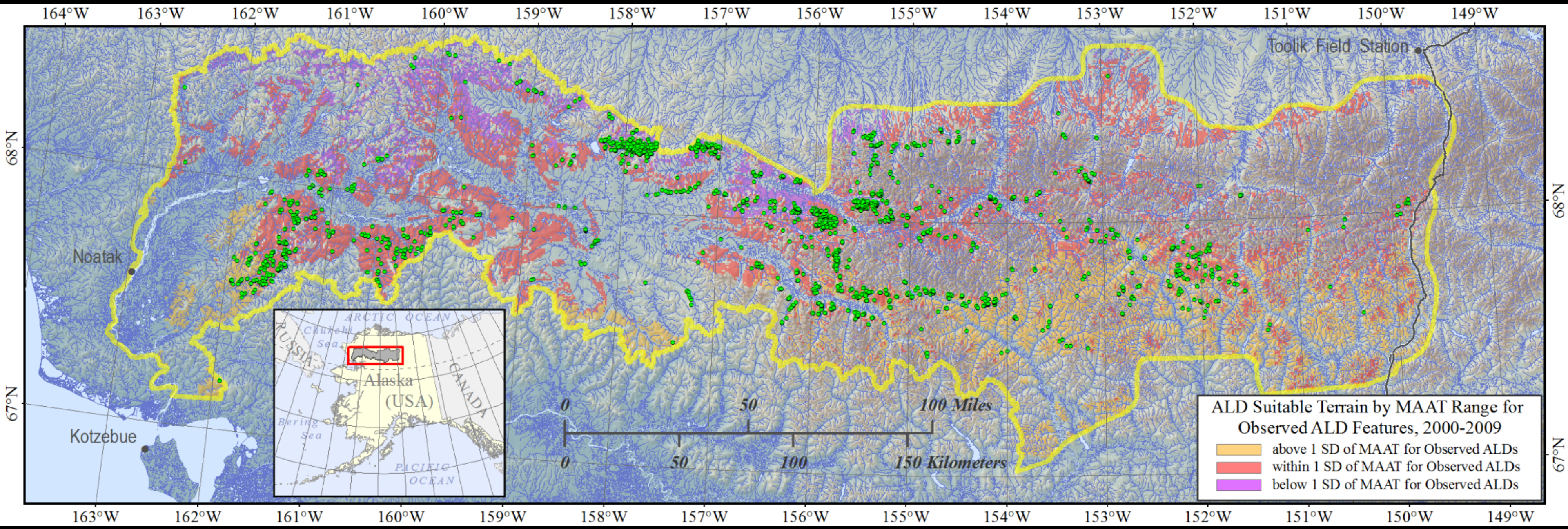
- Forecasting future conditions in the cryosphere depends on synthesizing weather and climate patterns with spatially explicit information on terrain suitability for different modes of permafrost degradation.


Questions?



Toolik Field Station
Noatak
Kotzebue
ARCTIC OCEAN
Chukchi Sea
RUSSIA
Alaska (USA)
CANADA
Bering Sea
PACIFIC OCEAN
0 50 100 Miles
0 50 100 150 Kilometers
ALD Suitable Terrain by MAAT Range for Observed ALD Features, 1910-1919
above 1 SD of MAAT for Observed ALDs
within 1 SD of MAAT for Observed ALDs
below 1 SD of MAAT for Observed ALDs
164°W 163°W 162°W 161°W 160°W 159°W 158°W 157°W 156°W 155°W 154°W 153°W 152°W 151°W 150°W 149°W
68°N
67°N


ALD Suitable Terrain by MAAT Range for Observed ALD Features, 2000-2009
above 1 SD of MAAT for Observed ALDs
within 1 SD of MAAT for Observed ALDs
below 1 SD of MAAT for Observed ALDs
Toolik Field Station
Noatak
Kotzebue
Alaska (USA)
ARCTIC OCEAN
RUSSIA
CANADA
Bering Sea
PACIFIC OCEAN
0 50 100 Miles
0 50 100 150 Kilometers
164°W 163°W 162°W 161°W 160°W 159°W 158°W 157°W 156°W 155°W 154°W 153°W 152°W 151°W 150°W 149°W
68°N
67°N



164°W
163°W
162°W
161°W
160°W
159°W
158°W
157°W
156°W
155°W
154°W
153°W
152°W
151°W
150°W
149°W
68°N
67°N
Toolik Field Station
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ARCTIC OCEAN
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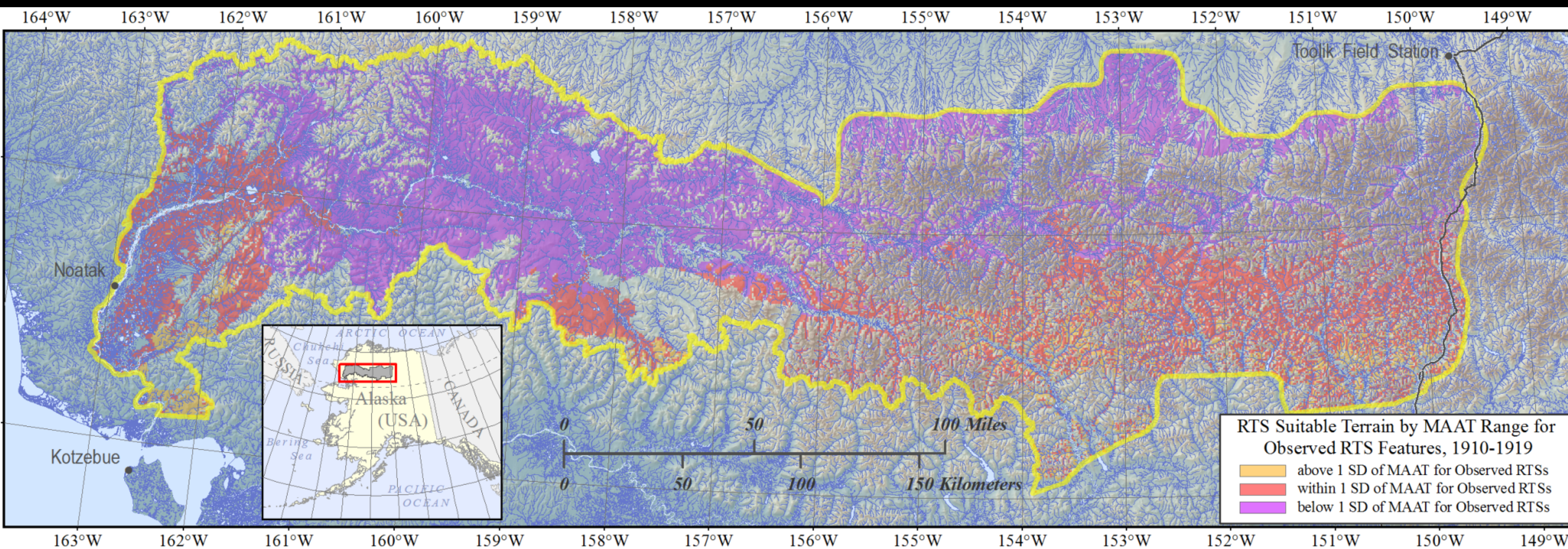
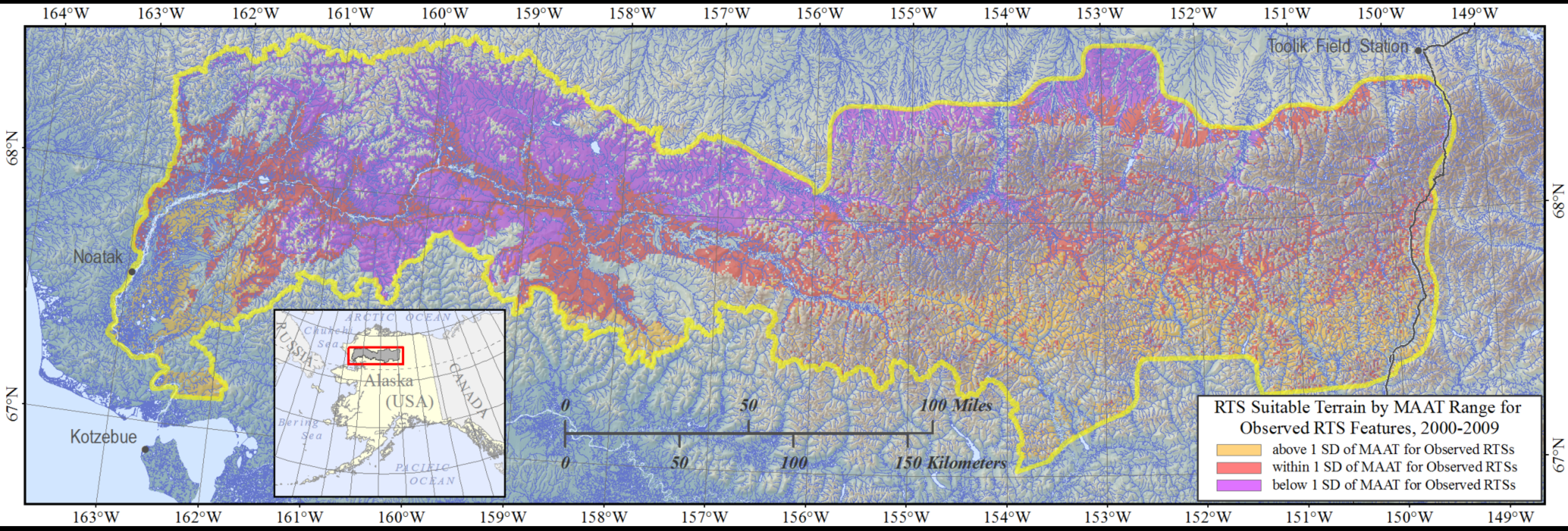
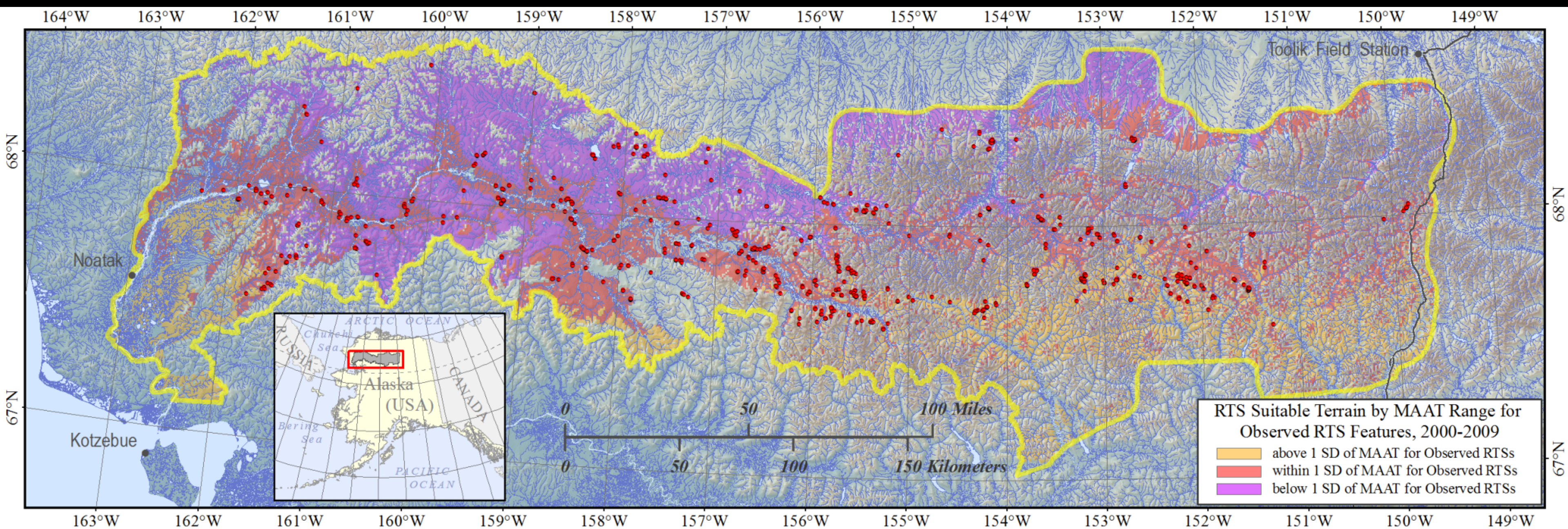
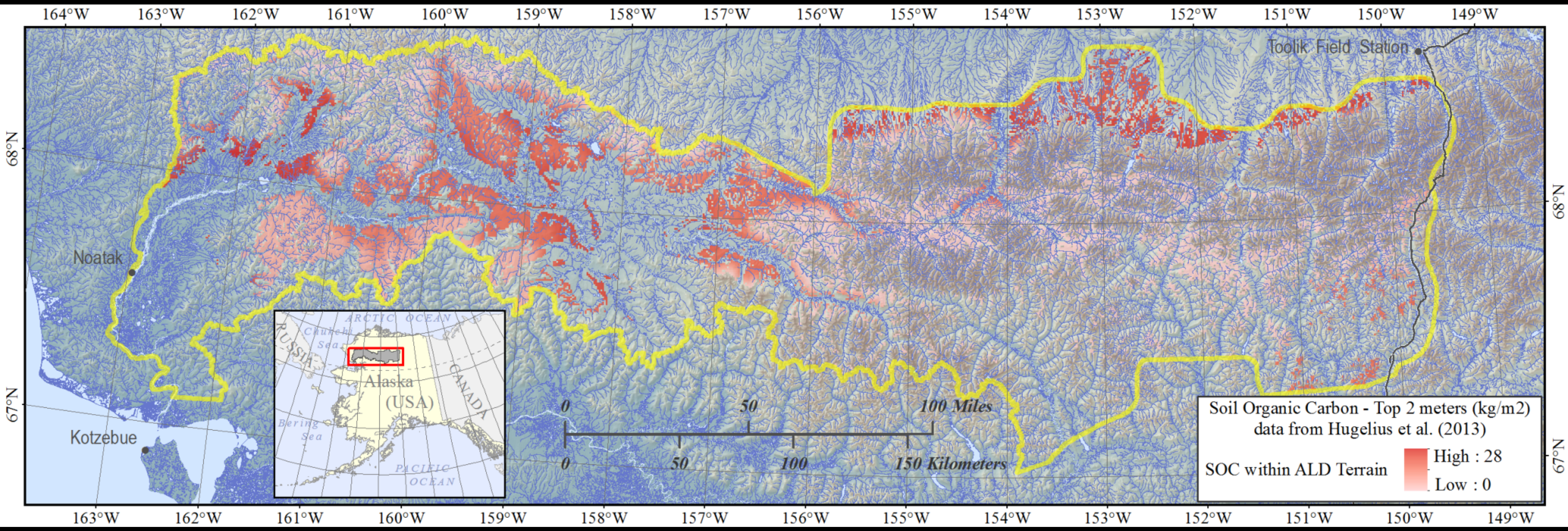
Chukchi Sea
Alaska (USA)
CANADA
Bering Sea
PACIFIC OCEAN
0
50
100 Miles
0
50
100
150 Kilometers
ALD Suitable Terrain by MAAT Range for Observed ALD Features, 2000-2009
above 1 SD of MAAT for Observed ALDs
within 1 SD of MAAT for Observed ALDs
below 1 SD of MAAT for Observed ALDs


164°W
163°W
162°W
161°W
160°W
159°W
158°W
157°W
156°W
155°W
154°W
153°W
152°W
151°W
150°W
149°W
68°N
67°N
Toolik Field Station
Noatak
Kotzebue
ARCTIC OCEAN
RUSSIA
Chukchi Sea
Alaska
(USA)
CANADA
Bering Sea
PACIFIC OCEAN
0
50
100 Miles
0
50
100
150 Kilometers
RTS Suitable Terrain by MAAT Range for
Observed RTS Features, 1910-1919
above 1 SD of MAAT for Observed RTSs
within 1 SD of MAAT for Observed RTSs
below 1 SD of MAAT for Observed RTSs

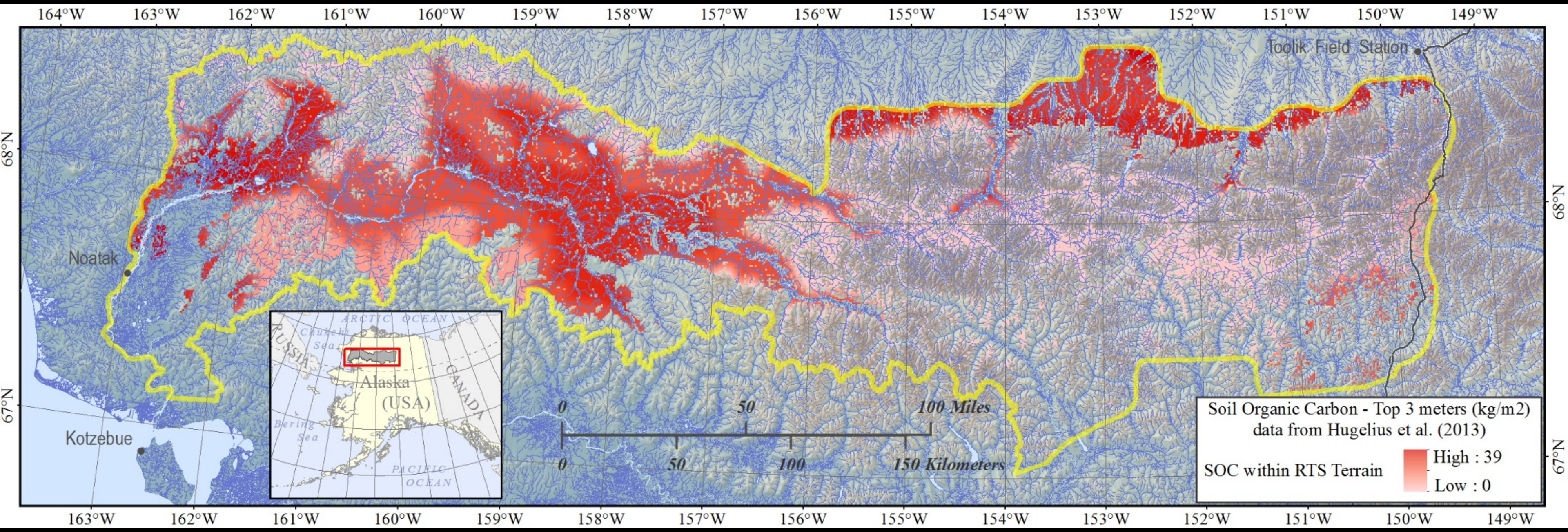

Toolik Field Station
Noatak
Kotzebue
ARCTIC OCEAN
RUSSIA
Chukchi Sea
Alaska (USA)
CANADA
Bering Sea
PACIFIC OCEAN
0 50 100 Miles
0 50 100 150 Kilometers
RTS Suitable Terrain by MAAT Range for Observed RTS Features, 2000-2009
above 1 SD of MAAT for Observed RTSs
within 1 SD of MAAT for Observed RTSs
below 1 SD of MAAT for Observed RTSs
164°W 163°W 162°W 161°W 160°W 159°W 158°W 157°W 156°W 155°W 154°W 153°W 152°W 151°W 150°W 149°W
68°N
67°N



164°W
163°W
162°W
161°W
160°W
159°W
158°W
157°W
156°W
155°W
154°W
153°W
152°W
151°W
150°W
149°W
68°N
67°N
Toolik Field Station
Noatak
Kotzebue
ARCTIC OCEAN
RUSSIA
Chukchi Sea
Alaska (USA)
CANADA
Bering Sea
PACIFIC OCEAN
0
50
100 Miles
0
50
100
150 Kilometers
RTS Suitable Terrain by MAAT Range for Observed RTS Features, 2000-2009
above 1 SD of MAAT for Observed RTSs
within 1 SD of MAAT for Observed RTSs
below 1 SD of MAAT for Observed RTSs



Toolik Field Station
Noatak
Kotzebue
ARCTIC OCEAN
RUSSIA
Alaska (USA)
CANADA
Bering Sea
PACIFIC OCEAN
0 50 100 Miles
0 50 100 150 Kilometers
Soil Organic Carbon - Top 2 meters (kg/m2)
data from Hugelius et al. (2013)
SOC within ALD Terrain
High : 28
Low : 0



Toolik Field Station
Noatak
Kotzebue
ARCTIC OCEAN
RUSSIA
Alaska (USA)
CANADA
Bering Sea
PACIFIC OCEAN
0 50 100 Miles
0 50 100 150 Kilometers
Soil Organic Carbon - Top 3 meters (kg/m2)
data from Hugelius et al. (2013)
SOC within RTS Terrain
High : 39
Low : 0

Acknowledgements

Committee:

Jay Jones, Advisor

Rudi Gens, Michelle Mack, Skip Walker

Funding and other Support:

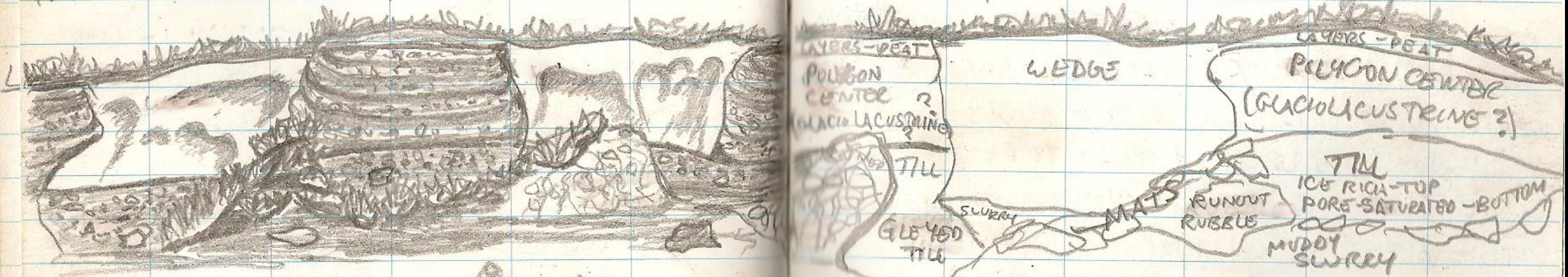
Center for Global Change (CGC)

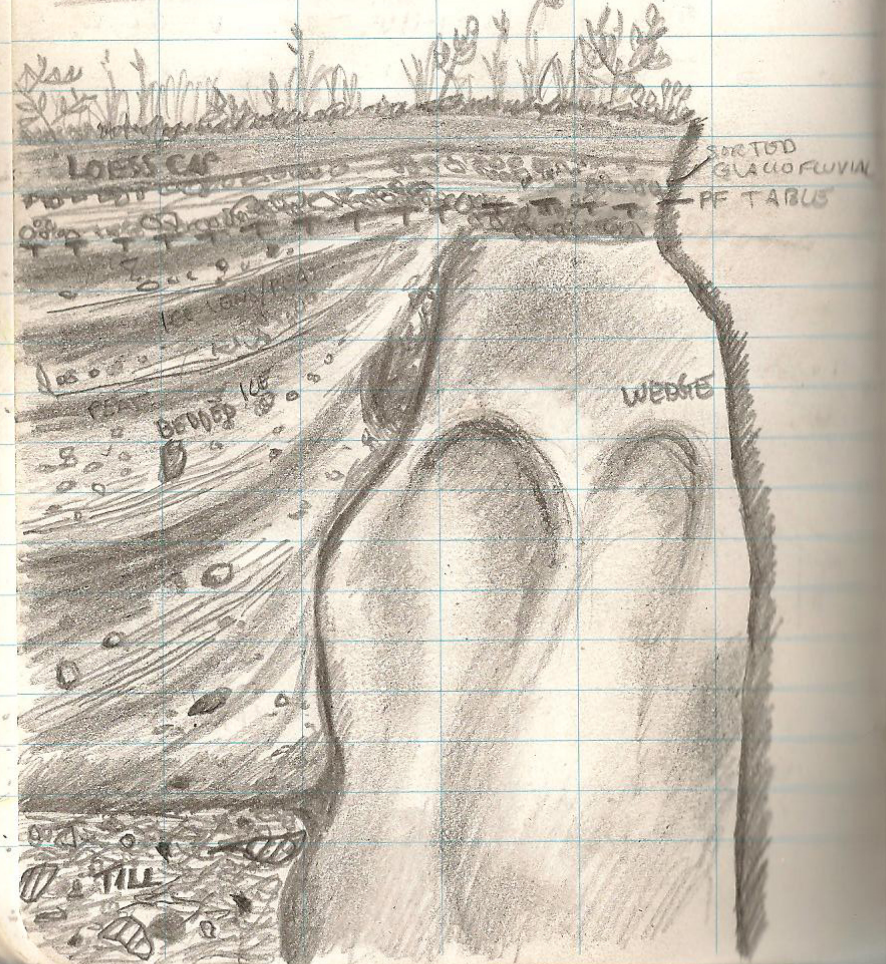
NSF Arctic System Science (ARCSS)

National Park Service Arctic Network (ARCN)

7/31/14

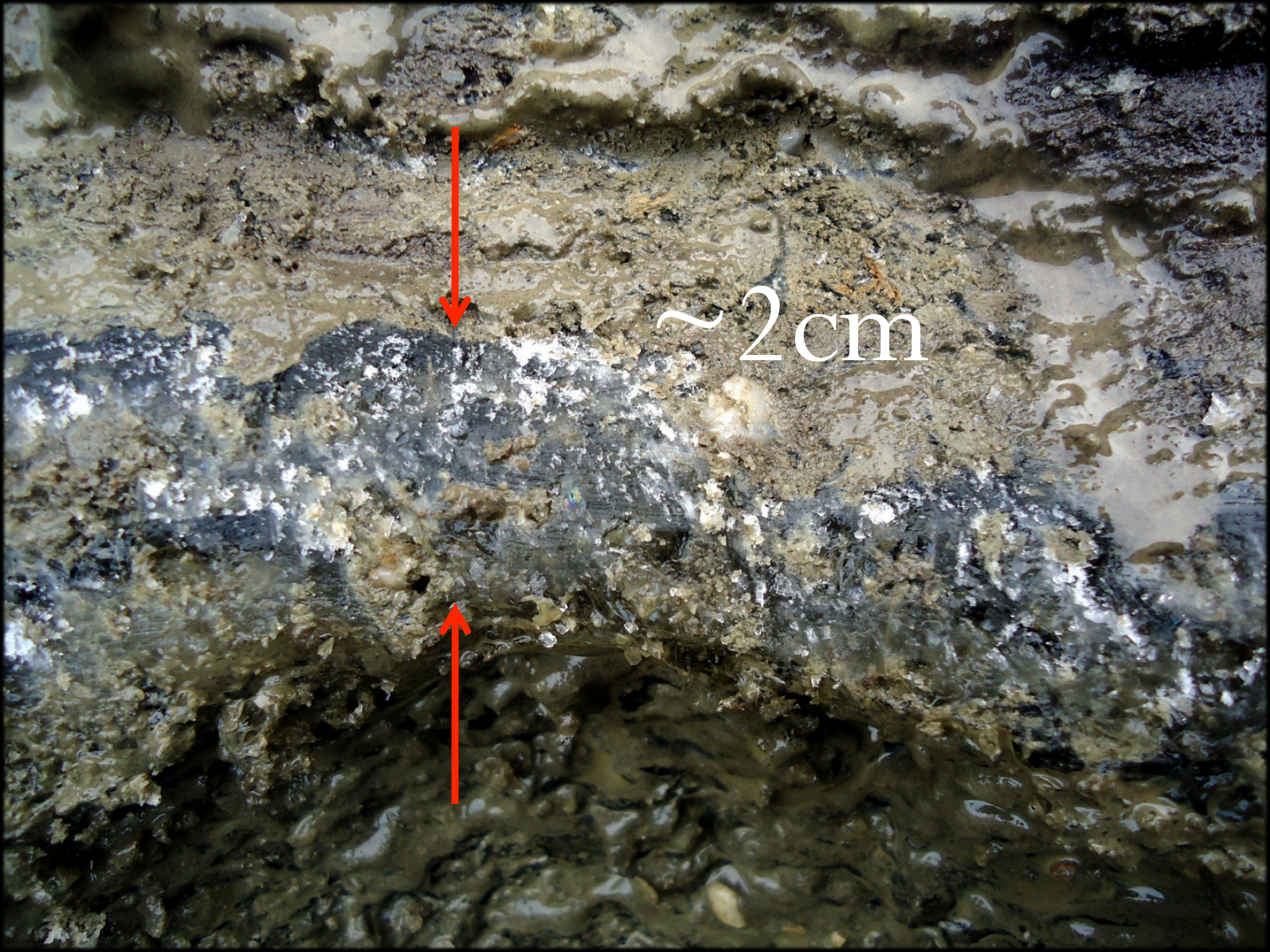
T2011-12 SCHEMATIC OF CENTRAL HEADWALL AND PANORAMA

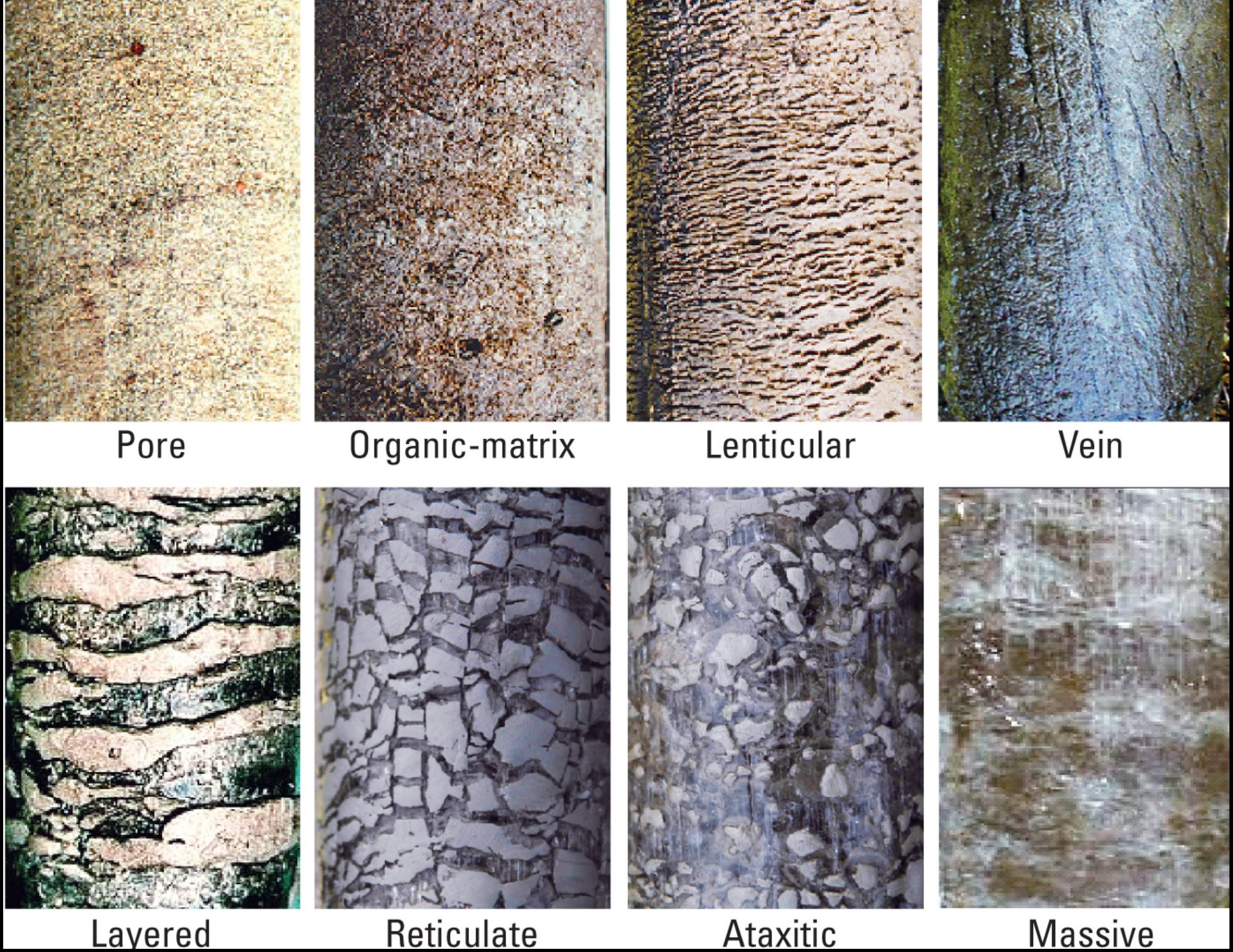




* WEDGES PENETRATE LOWER THAN FLOOR OF TK
* BASAL TILL ALMOST SLIMY WHEN SCRAPED IT'S SO ICE-RICH (PORE)

JUST ACROSS SMALL RIVER VALLEY FROM id1A TERMINAL MORAINE (~1 MILE FROM MORAINE CREST) T2011-12 APPEARS TO HAVE A TILL BASE (ODDLY UNIFORM DIAMICTOUS GREY, SILT RICH) WITH SUPER-SATURATED PORE ICE. TOP SECTION OF BASAL TILL HAS 25 - 200cm OF ATAXITIC (>65%) ICE. SEVERAL MORE LAYERS MAY BE TILL OR VERY PROXIMAL GLACIOLACUSTRINE, OR MAYBE GLACIOFLUVIAL OUTWASH. PREDOMINANTLY BEDDED (0.4-1.2 cm LENSES) INTERSPERSED WITH 4-10cm THICK ICE BEDS (GIVING THE STRIATED APPEARANCE IN HEADWALL. TOP ~1m HAS SOME OBVIOUS PROXIMAL AND DISTAL GLACIOLACUSTRINE WITH PEAT INTERLAIN. SOME PLACES SHOW ~20cm LOESS CAP UNDER LIVING VEGETATION. SOME PLACES SHOW PRONOUNCED SORTING OF ROUNDED CLASTS/SILT.


~2cm



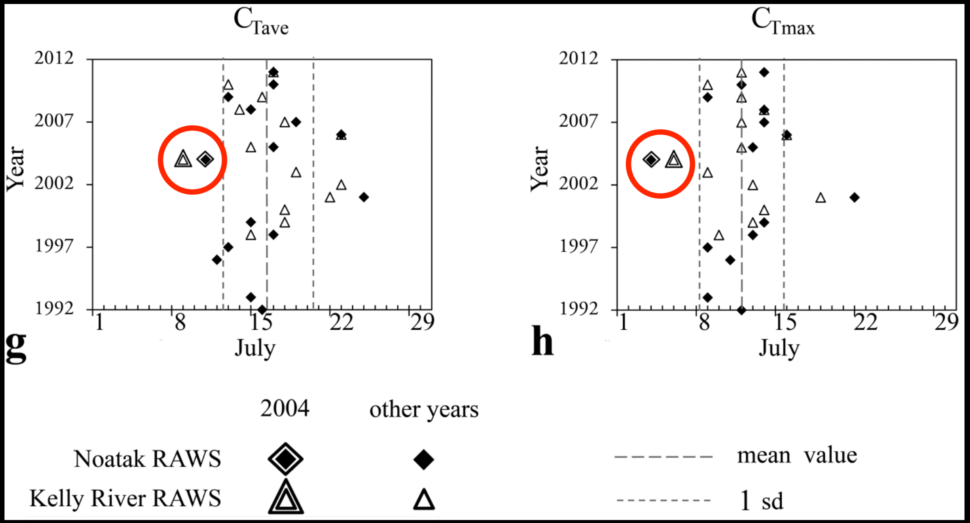
Heginbottom, J. A., J. Brown, O. Humlum, and B. H. Svensson (2012), PERMAFROST AND PERIGLACIAL ENVIRONMENTS, in *State of the Earth's cryosphere at the beginning of the 21st century–Glaciers, global snow cover, floating ice, and permafrost and periglacial environments*, edited by R. S. Williams, Jr. and J. G. Ferrigno, p. 546, U.S. Geological Survey Professional Paper 1386–A, Reston, VA.

For the central and western Brooks Range:

Where ALD and RTS features are most likely to occur.

When ALD and RTS features occur.

Median date of thawing temperatures, 1992 - 2012



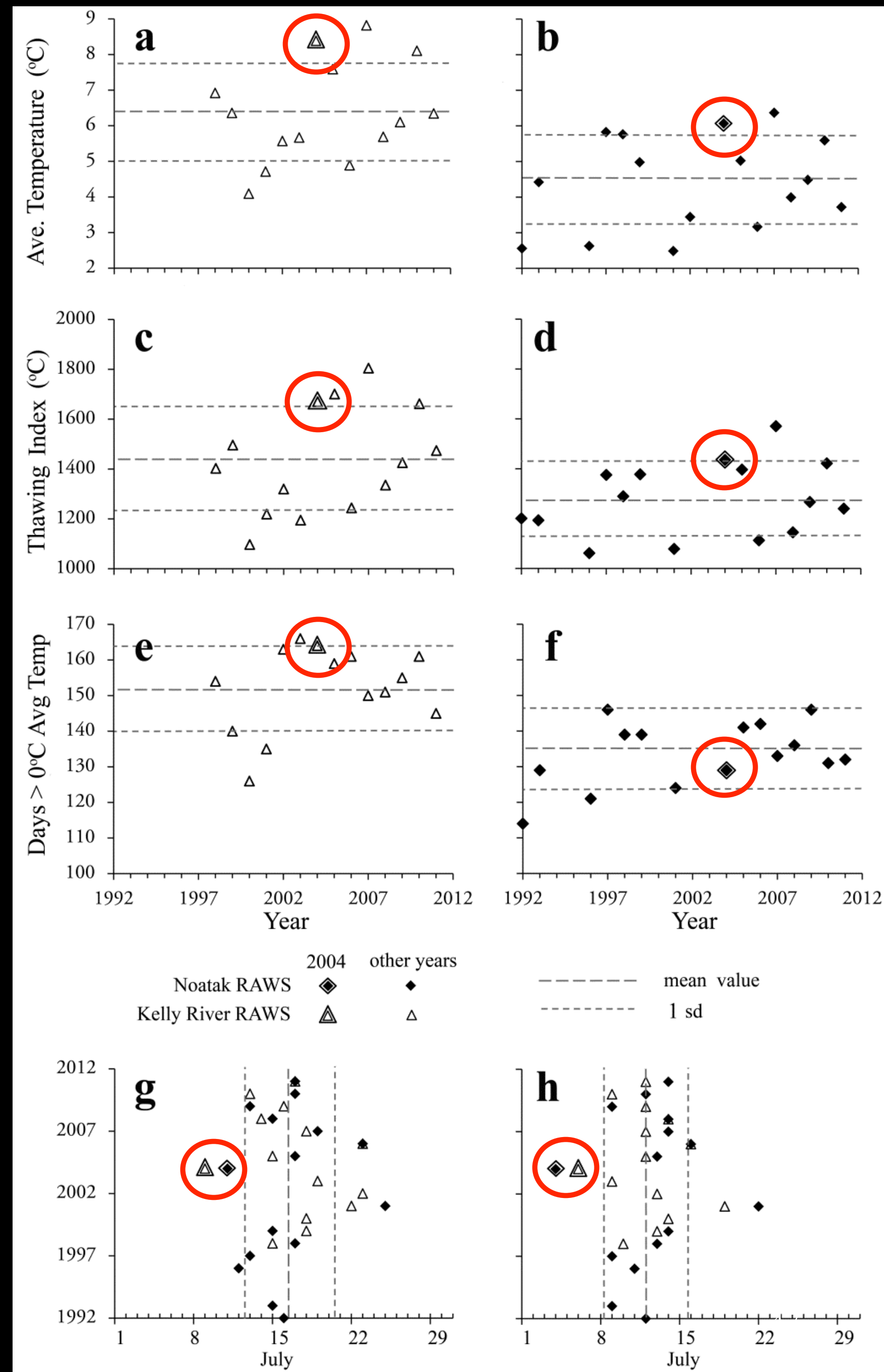
'Center of Mass Timing'

$$C_T = \sum (t_i q_i) / \sum q_i$$

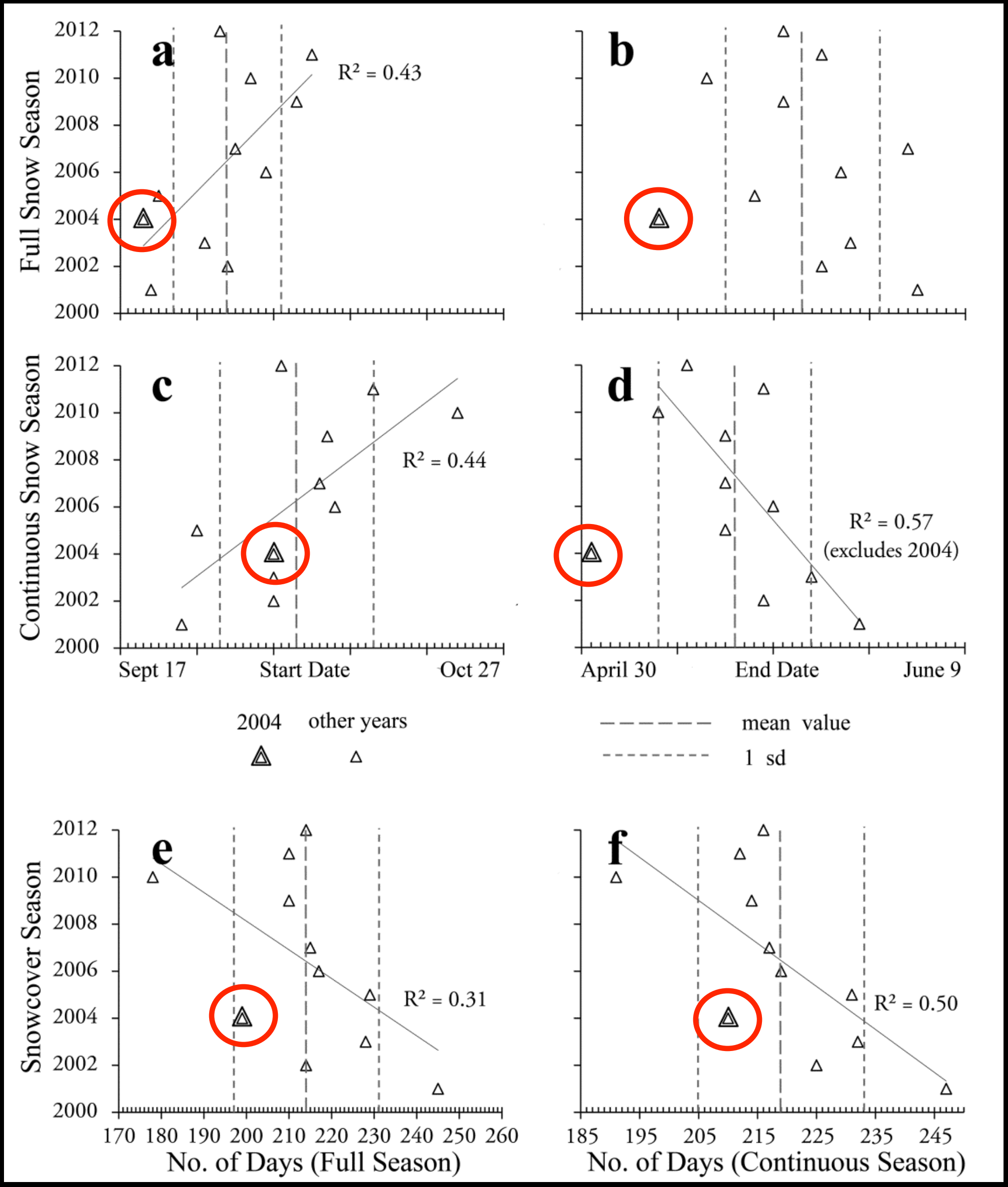
where t_i is day of year (Julian date) and q_i is thawing degree days on day t_i.

Adapted from: Stewart, I. T., D. R. Cayan, and M. D. Dettinger (2005), Changes toward earlier streamflow timing across western North America, *Journal of Climate, 18(8), 1136-1155*

- Ave Temp (°C, Thawing season)
- Thawing Index (°C)
- Days > 0°C Ave. Temp.
- C_T



- Full Snow Season
- Continuous Snow Season
- No. of Days in Snow Season



Trend lines are significant at $p<0.1$.

Full and Continuous Snow Season End Dates

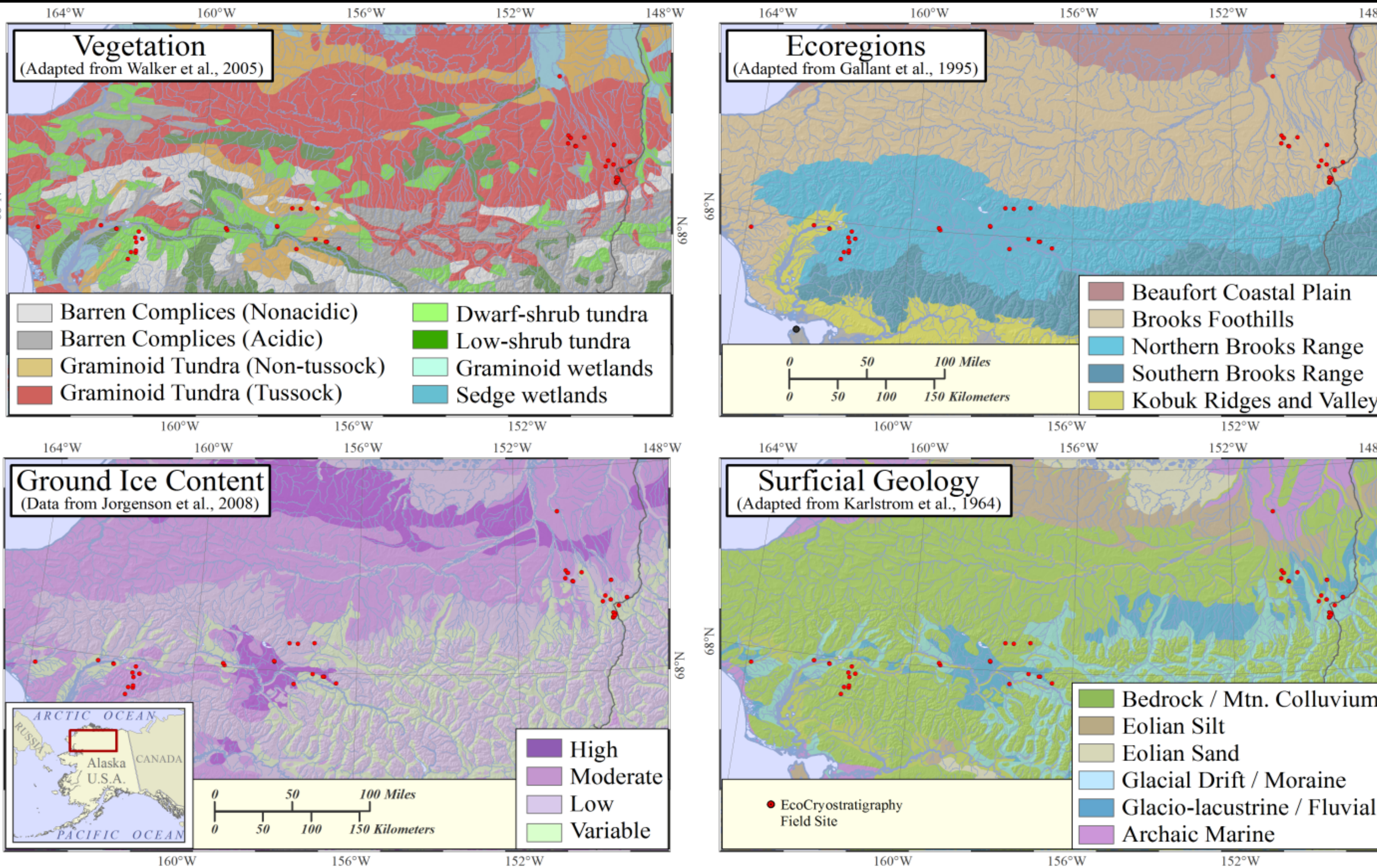
Analysis Boundary	FSS End 2001-2012 mean date (sd, days)	FSS End 2004 date (diff. from mean)	CSS End 2001-2012 mean date (sd, days)	CSS End 2004 date (diff. from mean)
Noatak & Wulik	May 23 (8)	May 8 (-15)	May 16 (8)	May 1 (-15)
Noatak	May 25 (8)	May 12 (-13)	May 18 (7)	May 6 (-12)

Maximum temperature and number of days with temperature above freezing

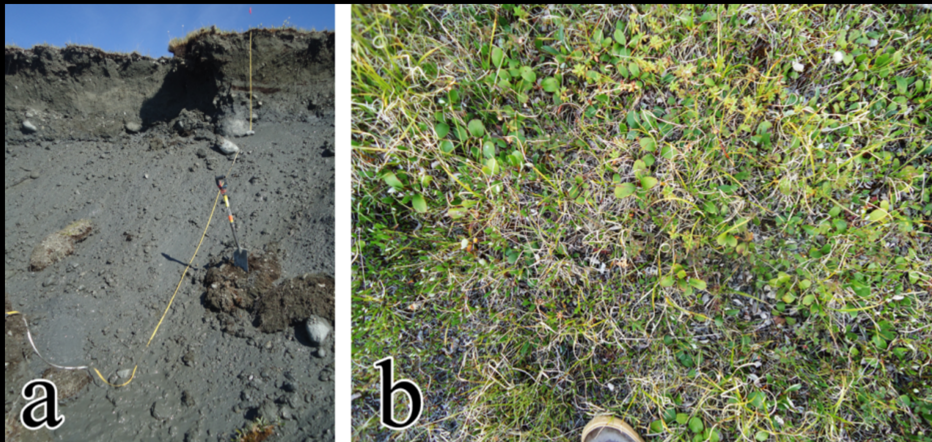
Station	April		May		June	
	Max. Temp.	Max > 0°C	Max. Temp.	Max > 0°C	Max. Temp.	Max > 0°C
	°C	No. of days	°C	No. of days	°C	No. of days
Kotzebue NOAA	5.0	20	12.7	31 +	28.9	30 +
Kelly River RAWS	9.4	24	22.2	31	30.6	30
Noatak RAWS	10.7	18	29.4 *	31 *	34.5	30
Bettles NOAA	10.5	26	21.6	31 +	31.1	30 +

* includes some gap-filled values

+ includes multiple record high temperatures


Vegetation
(Adapted from Walker et al., 2005)
Barren Complices (Nonacidic)
Barren Complices (Acidic)
Graminoid Tundra (Non-tussock)
Graminoid Tundra (Tussock)
Dwarf-shrub tundra
Low-shrub tundra
Graminoid wetlands
Sedge wetlands
Ecoregions
(Adapted from Gallant et al., 1995)
Beaufort Coastal Plain
Brooks Foothills
Northern Brooks Range
Southern Brooks Range
Kobuk Ridges and Valley
0 50 100 Miles
0 50 100 150 Kilometers
Ground Ice Content
(Data from Jorgenson et al., 2008)
High
Moderate
Low
Variable
ARCTIC OCEAN
RUSSIA
Alaska
U.S.A.
CANADA
PACIFIC OCEAN
Surficial Geology
(Adapted from Karlstrom et al., 1964)
EcoCryostratigraphy
Field Site
Bedrock / Mtn. Colluvium
Eolian Silt
Eolian Sand
Glacial Drift / Moraine
Glacio-lacustrine / Fluvial
Archaic Marine
164°W
160°W
156°W
152°W
148°W
68°N

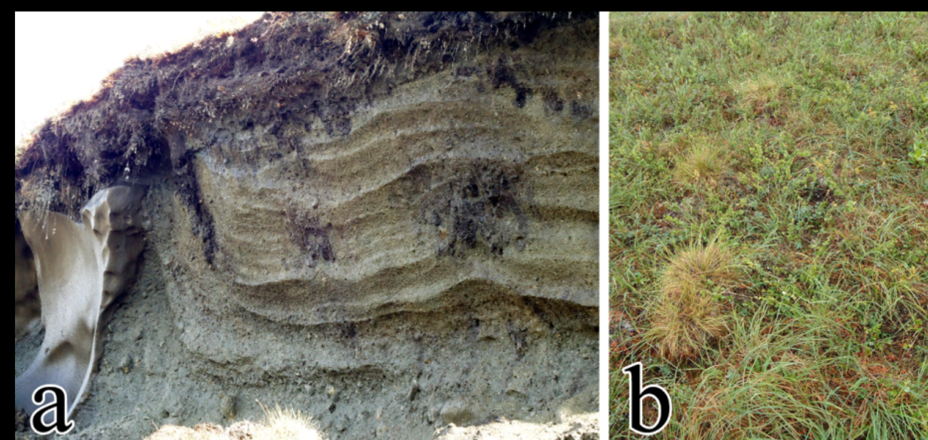
Photos 2a and 2b courtesy W. B. Bowden.



E1

E2

E3



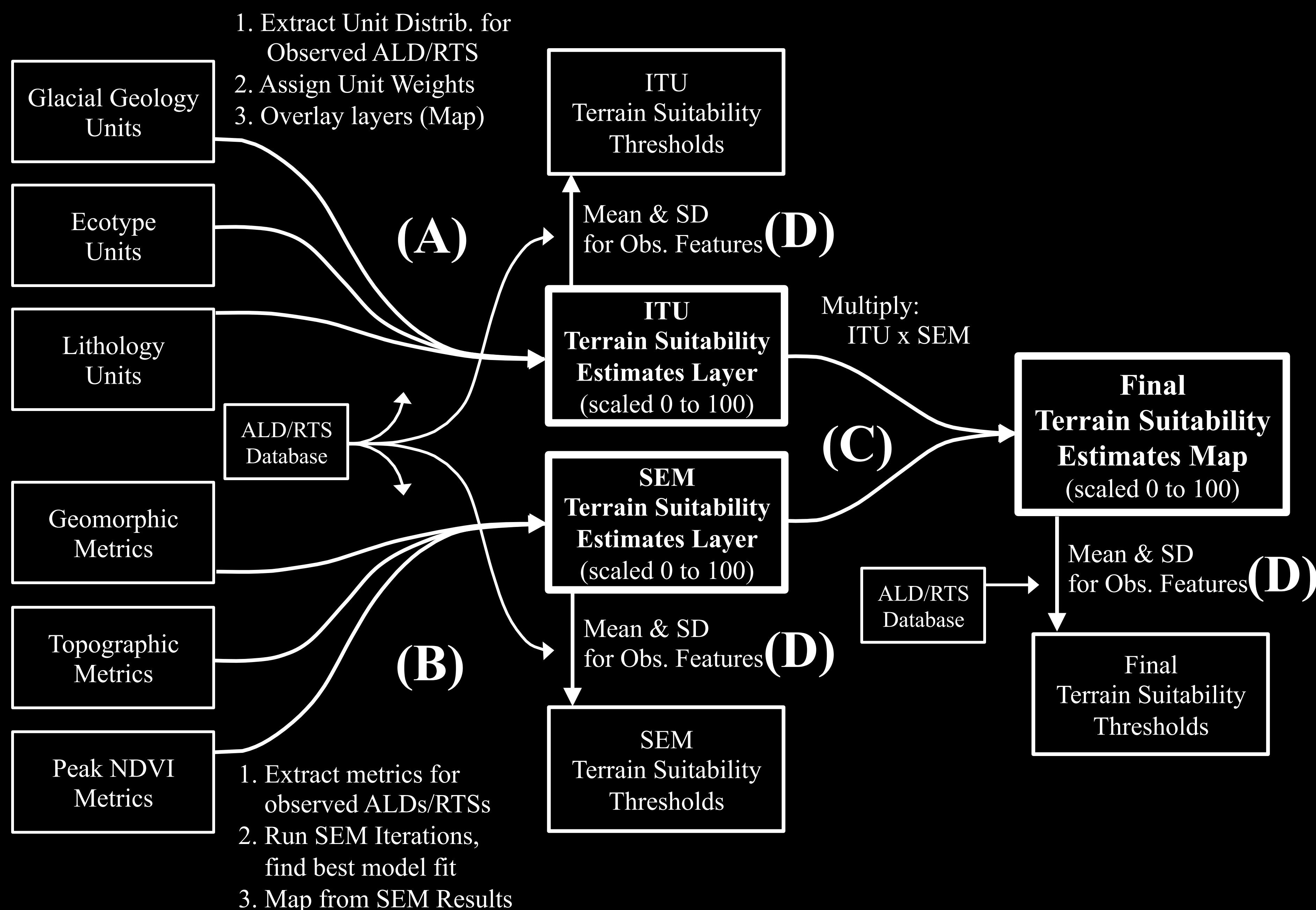
E4

Name	Block	Type	Class
Vegetation class	Vegetative	Categorical	Active
Acidic	Vegetative	Categorical	Active
Litter Layer Thickness (O_i)	Vegetative	Quantitative	Active
Organic Layer Thickness (O_a)	Vegetative	Quantitative	Active
Buried Organics Percentage	Vegetative	Quantitative	Active
Depth of Contemporary Soil	Substrate	Quantitative	Active
Depth of Active Layer	Substrate	Quantitative	Active
Coarse Fraction Percentage (contemporary soil)	Substrate	Quantitative	Active
Microtopography	Substrate	Categorical	Active
Coarse & Fine Fraction (contemporary soil)	Substrate	Categorical	Active
Coarse & Fine Fraction (archaic soil/parent material)	Substrate	Categorical	Active
Ice percentage	Ice	Quantitative	Active
Segregation Ice Maximum Lens Width	Ice	Quantitative	Active
Wedge/Intrusive Ice Percentage	Ice	Quantitative	Active
Total Depth of Profile	Ice	Quantitative	Active
Primary Cryostructures	Ice	Categorical	Active
Secondary Cryostructures	Ice	Categorical	Active
Acidity (mean Ecotype pH)	n/a	Quantitative	Supplemental
Elevation	n/a	Quantitative	Supplemental
Aspect	n/a	Quantitative	Supplemental
Topographic Position Index	n/a	Quantitative	Supplemental
Summer Warmth Index	n/a	Quantitative	Supplemental
Slope	n/a	Quantitative	Supplemental
Surficial Geology	n/a	Categorical	Supplemental
Bedrock Geology	n/a	Categorical	Supplemental
Glacial Geology	n/a	Categorical	Supplemental
Vegetation Complex	n/a	Categorical	Supplemental
Ecotype	n/a	Categorical	Supplemental
Lithology	n/a	Categorical	Supplemental
Macrotopography	n/a	Categorical	Supplemental
Permafrost Degradation Mode	n/a	Categorical	Supplemental

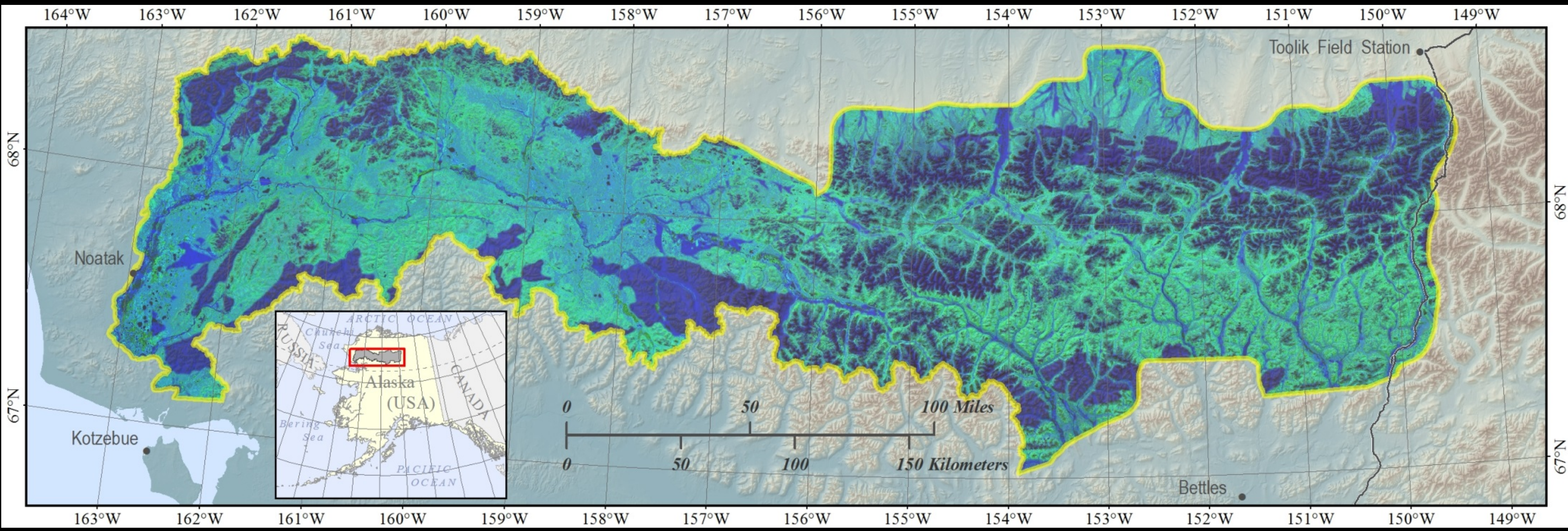
Segment	Name	Type		Source
Landscape	Physiographic position	Categorical	*	Table S1; Jorgenson et al., [2010b]
Landscape	Surficial Geology	Categorical	*	Hamilton, [2003 & 2010]
Landscape	Lithology	Categorical	*	Table S1; Jorgenson et al., [2010b]
Landscape	Bedrock Geology	Categorical	§	Beikman [1982]
Landscape	Glacial Geology	Categorical	§	Hamilton, [2003 & 2010]
Site Surface	Elevation	Quantitative	*	Garmin eTrex GPS
Landscape	Elevation	Quantitative	§	ASTER DEM
Site Surface	Slope	Quantitative	*	Brunton inclinometer
Landscape	Slope	Quantitative	§	ASTER DEM
Site Surface	Aspect	Quantitative	*	Brunton compass (declination adjusted)
Landscape	Aspect	Quantitative	§	ASTER DEM
Landscape	Topographic Position Index	Quantitative	§	ASTER DEM, Jenness [2006]
Landscape	Macrotopography	Categorical	*	Table S1; Jorgenson et al., [2010b]
Site Surface	Microtopography	Categorical	*	Table S1; Jorgenson et al., [2010b]
Landscape	Geomorphic unit	Categorical	*	Table S1; Jorgenson et al., [2010b]
Site Surface	Permafrost degradation mode	Categorical	*	Jorgenson et al., [2008]
Site Surface	Vegetation	Categorical	*	Viereck et al., [1992]; Jorgenson et al., [2010b]
Landscape	Vegetation complex	Categorical	§	Walker et al., [2002]; Jorgenson et al., [2010b]
Site Surface	Dominant flora [over & understory]	Species	*	Hulten [1968] & Parker [2006]
Landscape	Summer Warmth Index	Quantitative	§	Raynolds et al., [2008]
Site Surface	Ecotype	Categorical	*	Jorgenson et al., [2010b]
Site Surface	Acidic (from mean pH per Ecotype)	Categorical	*	Jorgenson et al., [2010b]

Name	Segment	Type		Integrator Variable	Units / Source
Depth of Active Layer	Profile	Quantitative			cm
Total Depth of Profile	Profile	Quantitative			cm
Wedge/Intrusive Ice Percentage	Profile	Quantitative			% of profile exposure
Litter Layer Thickness (O_i)	Soil	Quantitative			cm
Organic Layer Thickness (O_a)	Soil	Quantitative			cm
Depth of Contemporary Soil	Soil	Quantitative			cm
Coarse Fraction Percentage	Soil	Quantitative	§	Coarse & Fine Fraction	% of profile exposure
Maximum Clast Size	Soil	Quantitative	*		cm
Segregation Ice Percentage	Soil	Quantitative	*		% of profile exposure
Segregation Ice Max. Width	Soil	Quantitative	*		cm
Lithofacies	Soil	Categorical	§	Coarse & Fine Fraction	Table S1; Jorgenson et al., [2010b]
Coarse & Fine Fraction	Soil	Categorical			Table S1; Jorgenson et al., [2010b]
Coarse Fraction Shape	Soil	Ordinal	*		Table S1; Jorgenson et al., [2010b]
Peat Type	Soil	Categorical	*		Table S1; Jorgenson et al., [2010b]
Primary Cryostructures	Parent	Categorical			Table S1; Jorgenson et al., [2010b]
Secondary Cryostructures	Parent	Categorical	*		Table S1; Jorgenson et al., [2010b]
Lithofacies	Parent	Categorical	§	Coarse & Fine Fraction	Table S1; Jorgenson et al., [2010b]
Coarse & Fine Fraction	Parent	Categorical			Table S1; Jorgenson et al., [2010b]
Coarse Fraction Shape	Parent	Ordinal			Table S1; Jorgenson et al., [2010b]
Buried Organics Percentage	Parent	Quantitative			% of profile exposure
Primary Cryostructures	Parent	Categorical			Table S1; Jorgenson et al., [2010b]
Secondary Cryostructures	Parent	Categorical			Table S1; Jorgenson et al., [2010b]
Coarse Fraction Percentage	Parent	Quantitative	§	Coarse & Fine Fraction	% of profile exposure
Maximum Clast Size	Parent	Quantitative	§	Coarse & Fine Fraction	cm
Segregation Ice Percentage	Parent	Quantitative			% of profile exposure
Segregation Ice Max. Width	Parent	Quantitative			cm

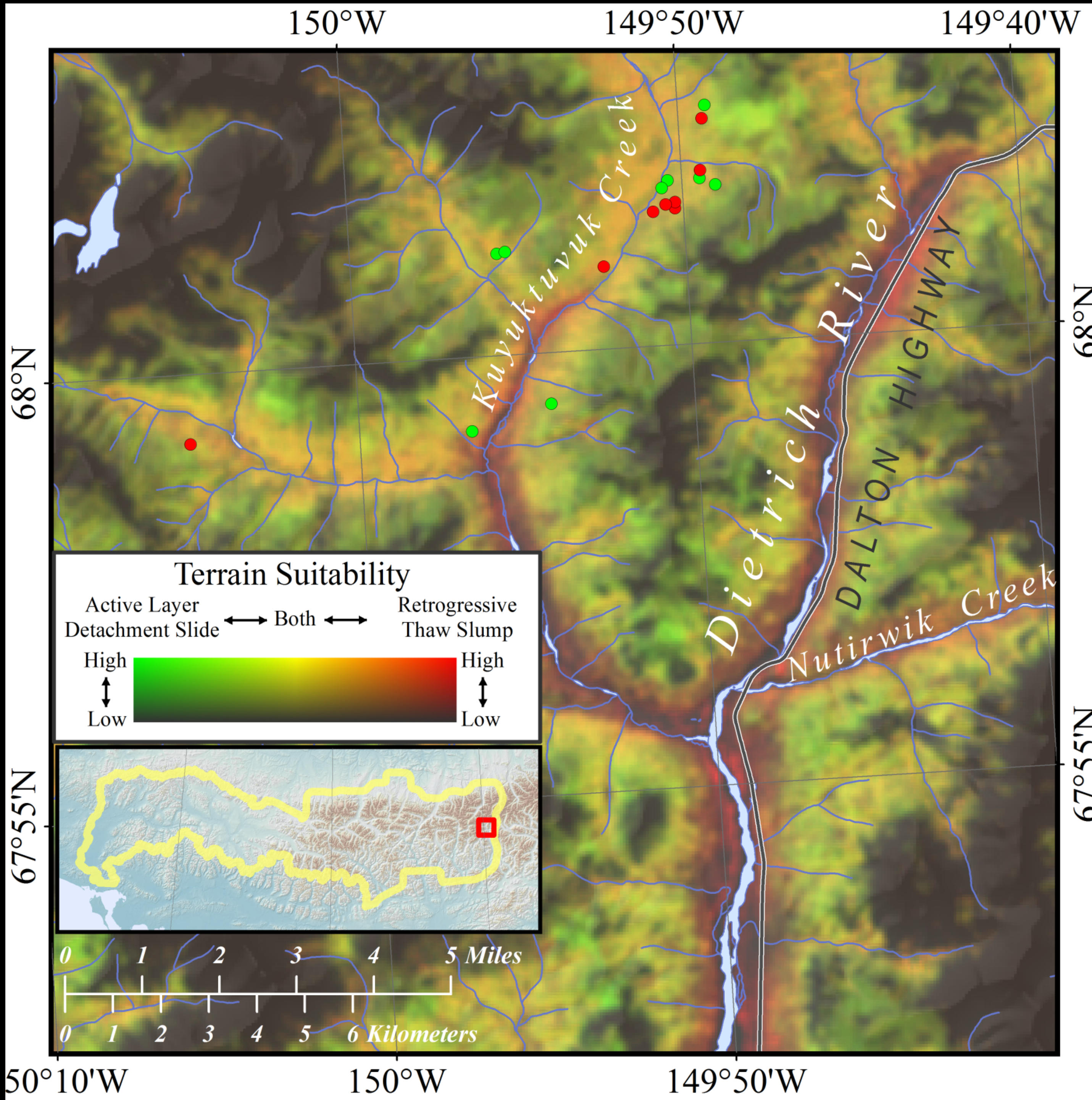
Site Grouping	Permafrost Degradation Mode				
	ALDS	Soil Pit	RTS	TEG	Total
E1	0	0	6	0	6
E2a	4	0	1	2	7
E2b	2	1	6	8	17
E3	7	0	2	0	9
E4a	0	0	3	0	3
E4b	0	0	9	1	10
E4c	0	0	2	0	2
Total	13	1	29	11	

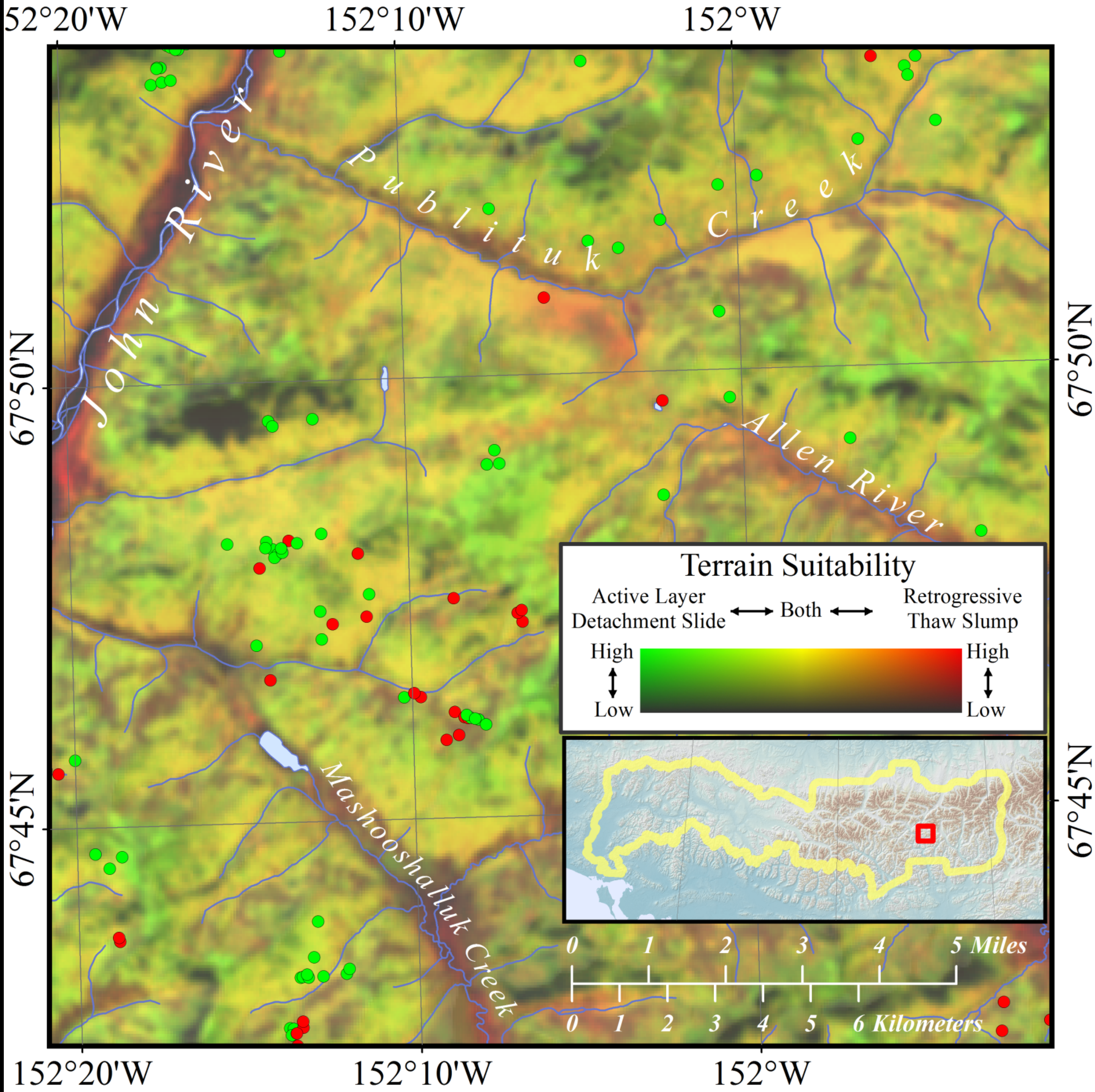

Glacial Geology Units
Ecotype Units
Lithology Units
ALD/RTS Database
Geomorphic Metrics
Topographic Metrics
Peak NDVI Metrics
1. Extract Unit Distrib. for Observed ALD/RTS
2. Assign Unit Weights
3. Overlay layers (Map)
(A)
ITU Terrain Suitability Thresholds
Mean & SD for Obs. Features
(D)
ITU Terrain Suitability Estimates Layer (scaled 0 to 100)
Multiply: ITU x SEM
(C)
SEM Terrain Suitability Estimates Layer (scaled 0 to 100)
Mean & SD for Obs. Features
(D)
(B)
SEM Terrain Suitability Thresholds
1. Extract metrics for observed ALDs/RTSs
2. Run SEM Iterations, find best model fit
3. Map from SEM Results
Final Terrain Suitability Estimates Map (scaled 0 to 100)
ALD/RTS Database
Mean & SD for Obs. Features
(D)
Final Terrain Suitability Thresholds

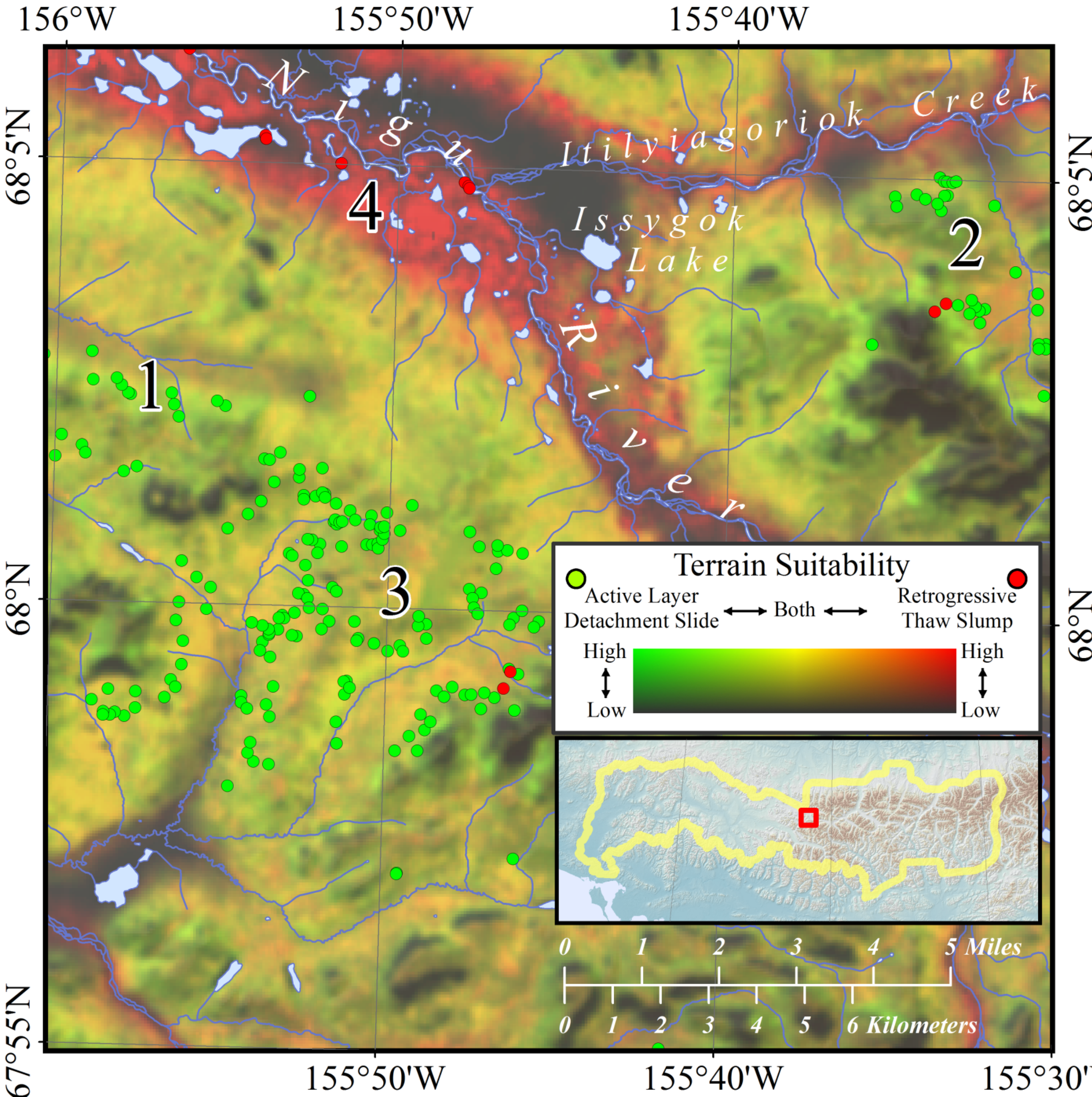
Ecotype	% of Study Region	% of RTS Features	% Differential	% of ALD Features	% Differential
Alpine Dryas Dwarf Shrub	19.0	15.7	0.8	20.0	1.1
Alpine Ericaceous Dwarf Shrub	0.0	0.0	0.0	5.0	2.5
Alpine Ericaceous Dwarf Shrub	2.0	2.8	1.4	0.0	0.0
Alpine Wet Sedge Meadow	1.0	1.0	1.0	1.0	1.5
Lowland Birch-Ericaceous-Willow Low Shrub	3.0	2.4	0.8	0.0	0.0
Lowland Sedge Fen	1.0	2.8	2.8	0.0	0.0
Riverine Alder or Willow Tall Shrub	1.0	1.6	1.6	0.0	0.0
Riverine Birch-Willow Low Shrub	1.0	2.0	2.0	0.0	0.0
Riverine Wet Sedge Meadow	1.0	1.2	1.2	0.0	0.0
Riverine Willow Low Shrub	1.0	0.9	0.9	0.0	0.0
Upland Alder-Willow Tall Shrub	4.0	6.8	1.7	9.0	2.3
Upland Birch-Ericaceous-Willow Low Shrub	12.0	23.7	2.0	23.0	1.9
Upland Dwarf Birch-Tussock Shrub	19.0	19.2	1.0	29.0	1.5
Upland Sedge-Dryas Meadow	6.0	9.6	1.6	6.0	1.0
Upland White Spruce Forest	4.0	3.0	0.8	1.0	0.3
Upland Willow Low Shrub	0.0	0.0	0.0	3.0	1.5
Upland Willow Low Shrub	2.0	2.9	1.4	0.0	0.0
Surficial Geology	**% of Study Region**	**% of RTS Features**	**% Differential**	**% of ALD Features**	**% Differential**
Alluvium	6.1	7.0	1.1	1.0	0.2
Thin Soil over Near-surface Bedrock	53.8	26.0	0.5	54.0	1.0
Colluvium	6.9	7.0	1.0	20.0	2.9
Glacial Drift	16.4	46.0	2.8	22.0	1.3
Fan Deposits	1.8	0.3	0.2	0.2	0.1
Gravel	0.1	0.1	0.7	0.0	0.0
Ice Contact	0.5	1.0	2.1	0.0	0.1
Inwash / Outwash	1.5	0.4	0.3	0.1	0.1
Lacustrine / Glaciolacustrine	9.4	11.0	1.2	2.0	0.2
Organic	0.0	0.0	0.0	0.0	0.0
Other (Active Glacier / Snowfield)	0.7	0.0	0.0	0.5	0.7
Sand	0.6	0.2	0.3	0.0	0.0
Silt	1.0	0.0	0.0	0.0	0.0
Terrace	1.2	1.0	0.8	0.0	0.0
Lithology	**% of Study Region**	**% of RTS Features**	**% Differential**	**% of ALD Features**	**% Differential**
Noncarbonate	89.8	99.2	1.1	98.3	1.1
Carbonate	10.2	0.8	0.1	1.7	0.2



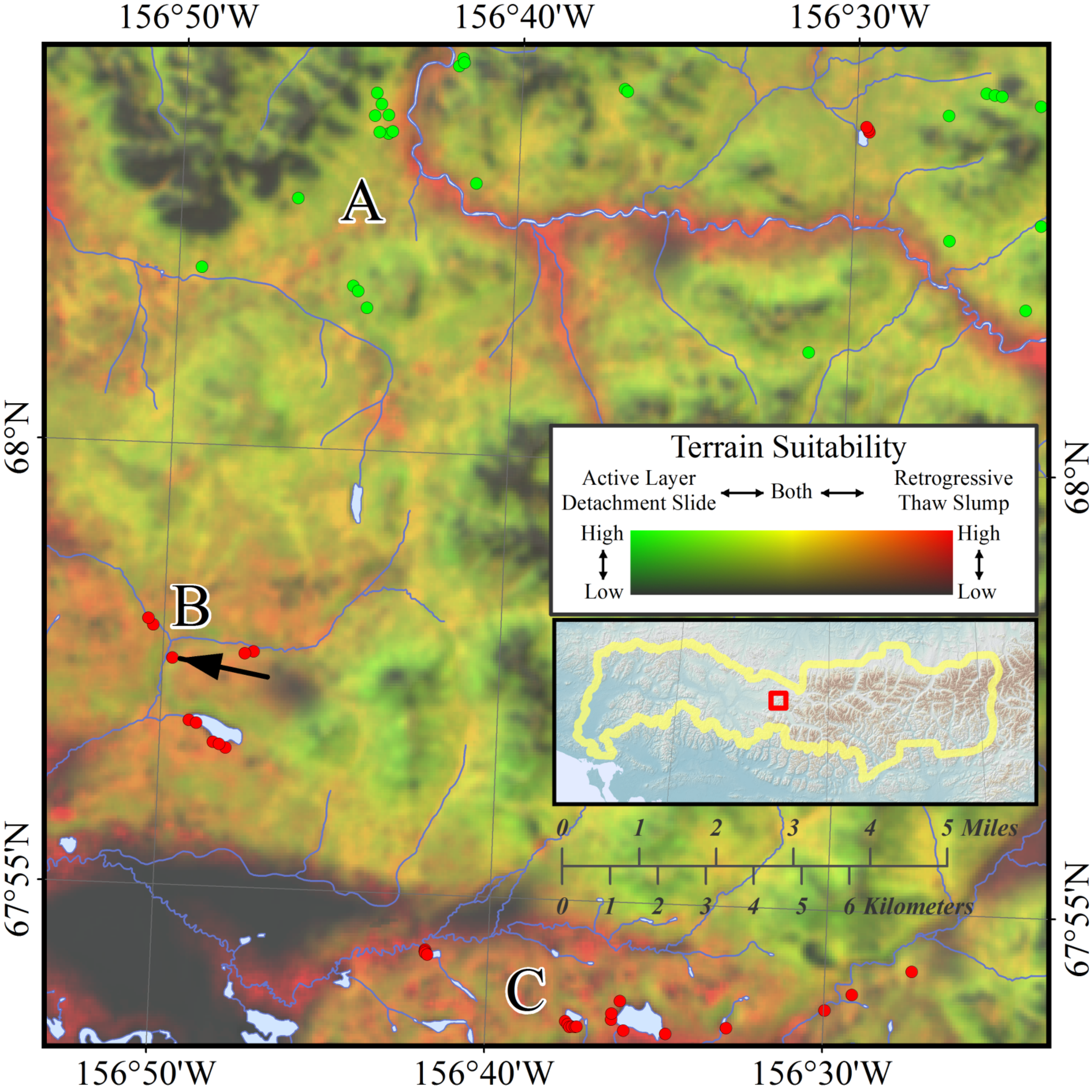
Toolik Field Station
Noatak
Kotzebue
Bettles
ARCTIC OCEAN
RUSSIA
Chukchi Sea
Alaska
(USA)
CANADA
Bering Sea
PACIFIC OCEAN
0
50
100 Miles
0
50
100
150 Kilometers
164°W
163°W
162°W
161°W
160°W
159°W
158°W
157°W
156°W
155°W
154°W
153°W
152°W
151°W
150°W
149°W
68°N
67°N

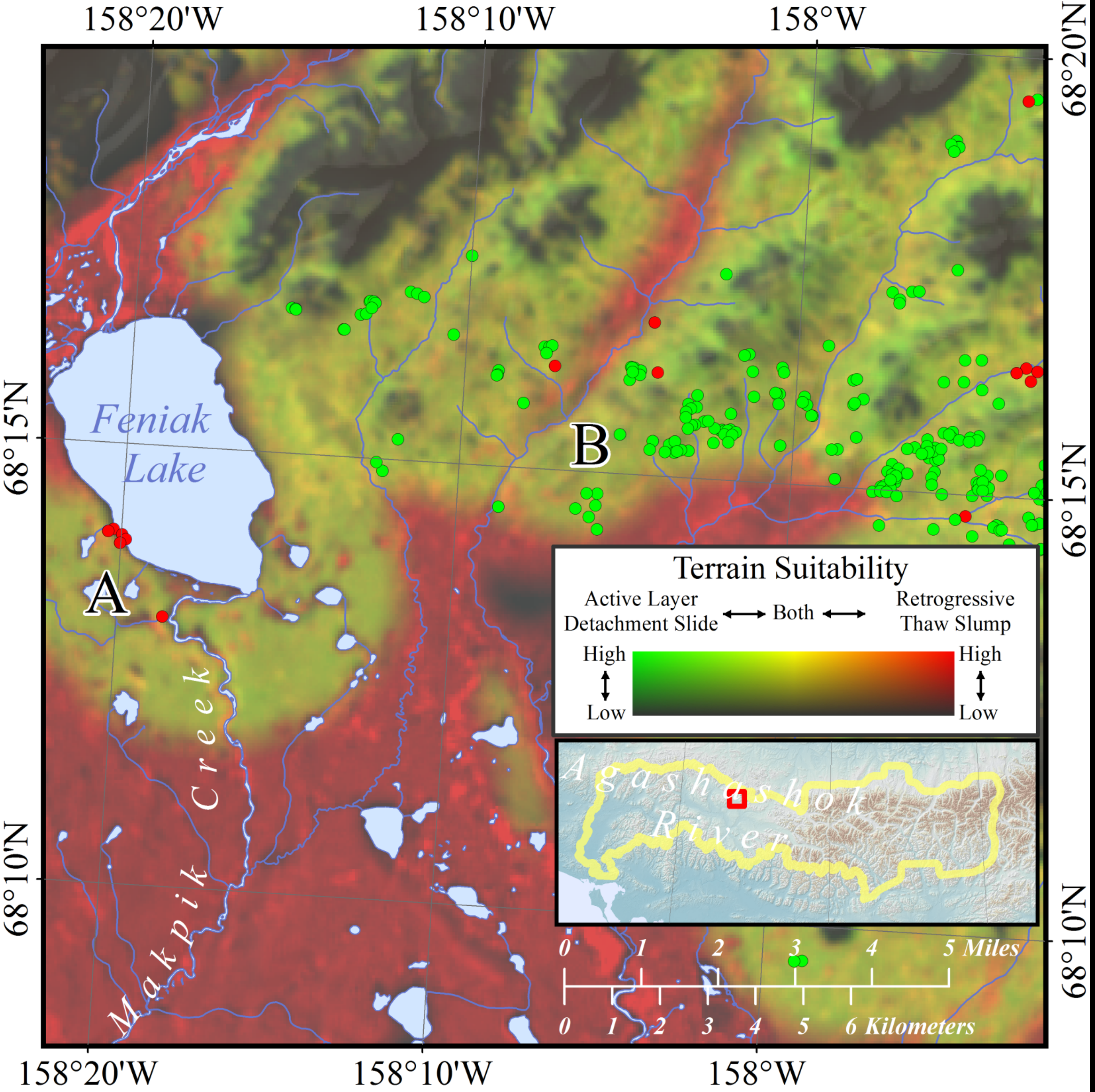

150°W
149°50'W
149°40'W
68°N
67°55'N
150°10'W
Kuyuktuvuk Creek
Dietrich River
DALTON HIGHWAY
Nutirwik Creek
Terrain Suitability
Active Layer Detachment Slide
Both
Retrogressive Thaw Slump
High
Low
High
Low
0 1 2 3 4 5 Miles
0 1 2 3 4 5 6 Kilometers

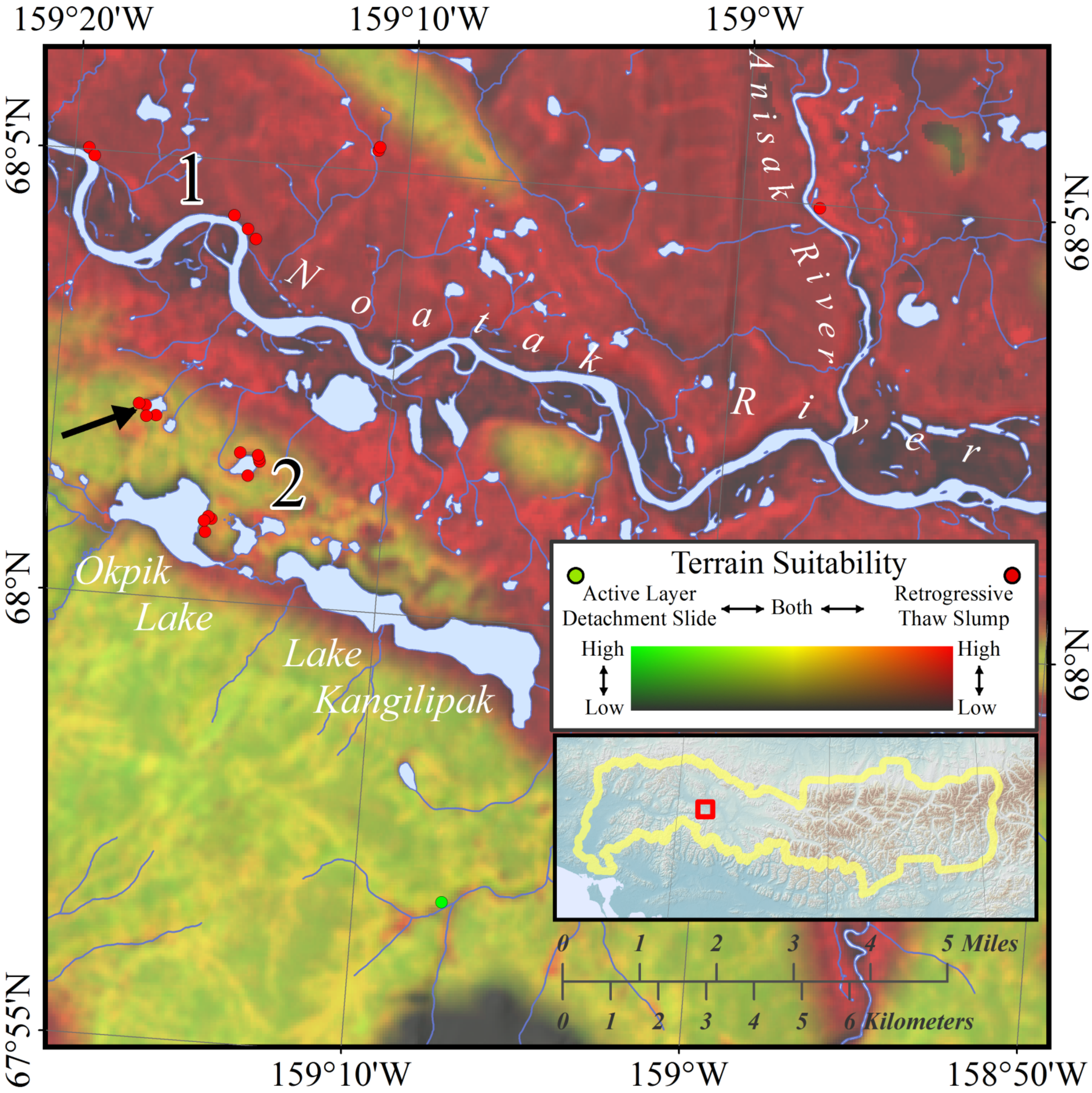

52°20'W
152°10'W
152°W
67°50'N
67°45'N
152°20'W
John River
Publituk Creek
Allen River
Mashooshalluk Creek
Terrain Suitability
Active Layer Detachment Slide
Both
Retrogressive Thaw Slump
High
Low
High
Low
0 1 2 3 4 5 Miles
0 1 2 3 4 5 6 Kilometers



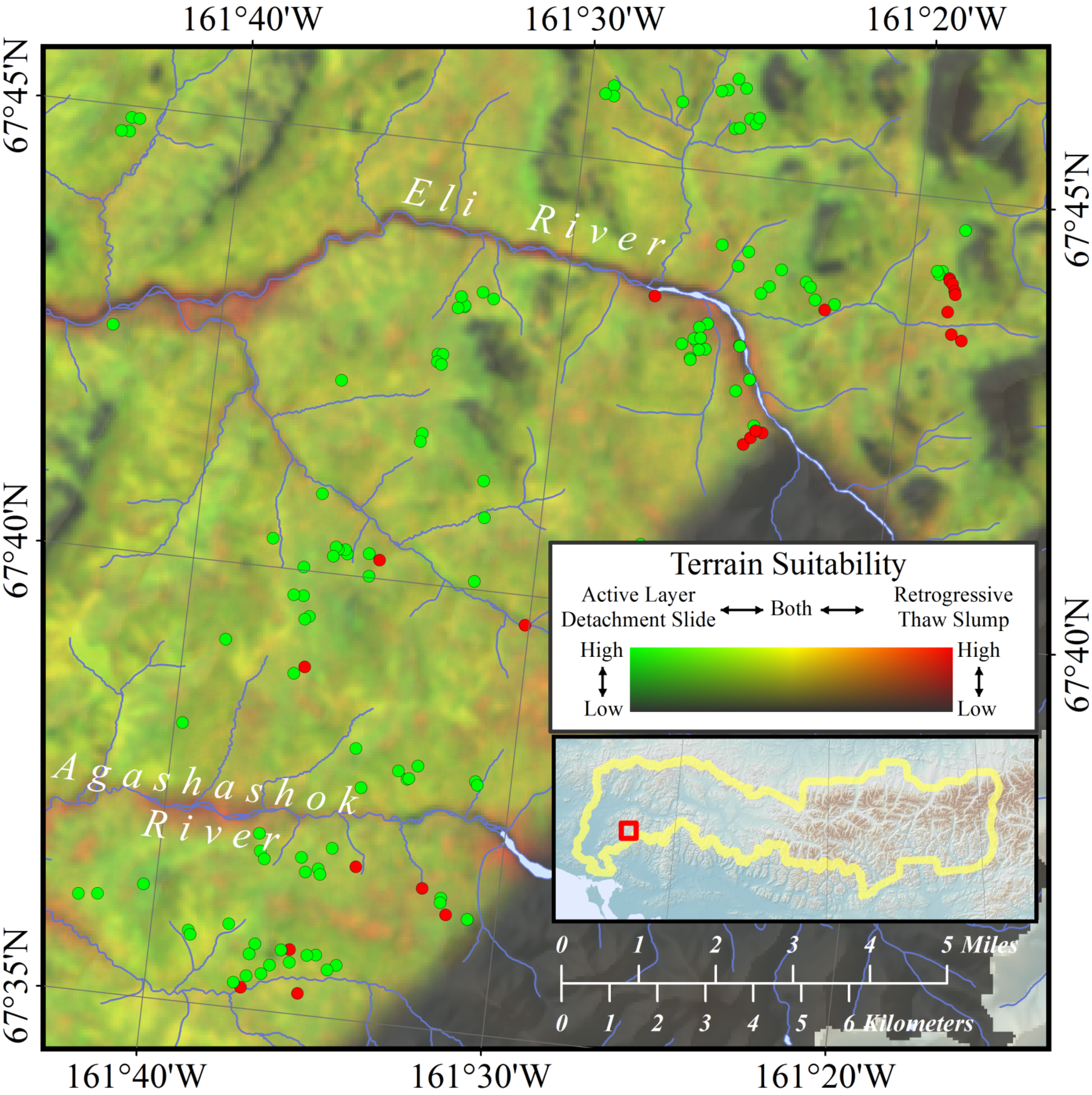
156°W
155°50'W
155°40'W
68°5'N
68°N
67°55'N
155°30'W
Nigu
Itilyiagoriok Creek
Issygok Lake
River
1
2
3
4
Terrain Suitability
Active Layer Detachment Slide
Both
Retrogressive Thaw Slump
High
Low
0 1 2 3 4 5 Miles
0 1 2 3 4 5 6 Kilometers

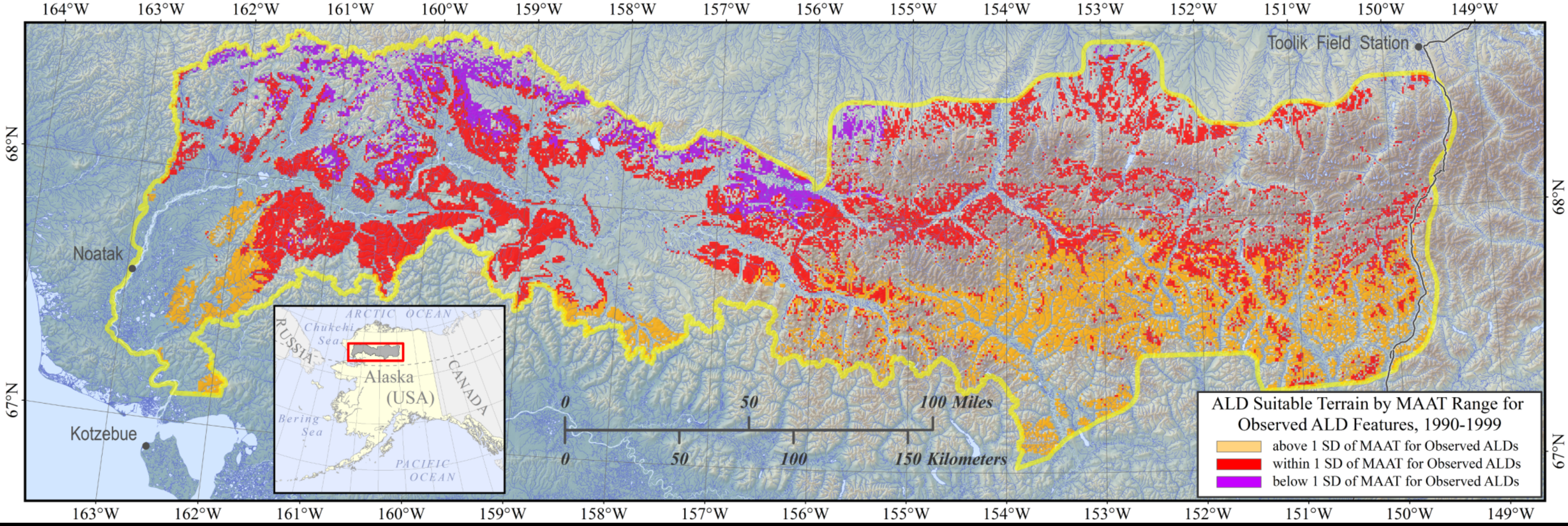

156°50'W
156°40'W
156°30'W
68°N
67°55'N
A
B
C
Terrain Suitability
Active Layer Detachment Slide
Both
Retrogressive Thaw Slump
High
Low
High
Low
0 1 2 3 4 5 Miles
0 1 2 3 4 5 6 Kilometers

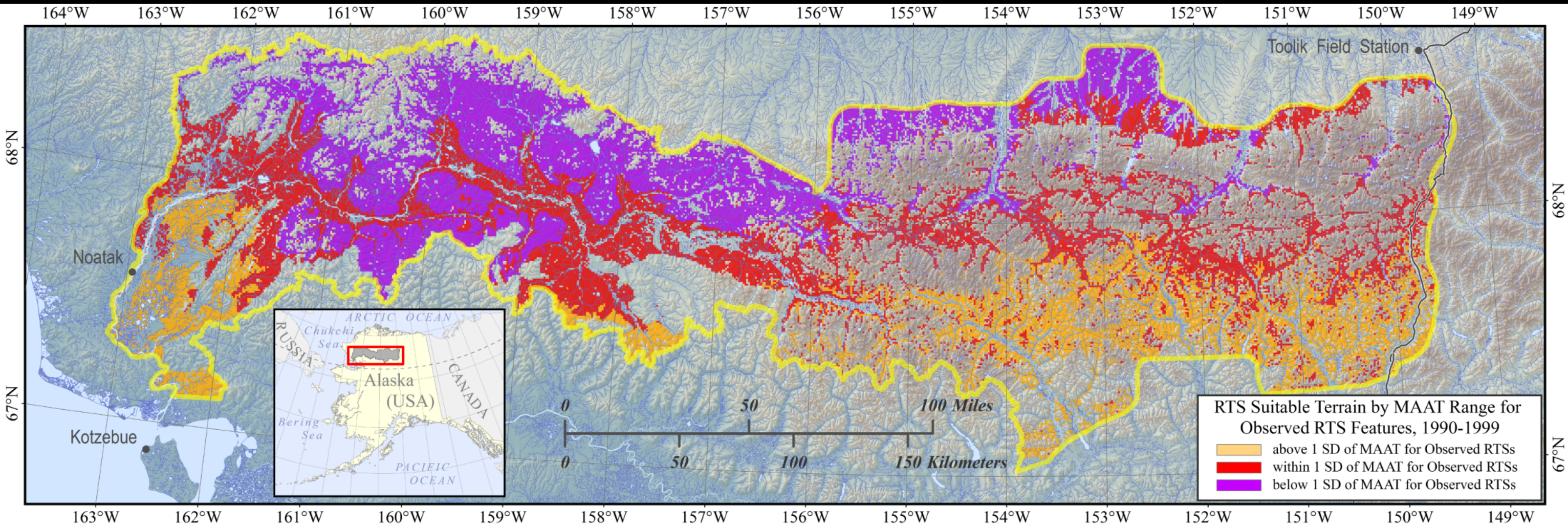

158°20'W
158°10'W
158°W
68°20'N
68°15'N
68°10'N
Feniak Lake
Makpik Creek
A
B
Terrain Suitability
Active Layer Detachment Slide
Both
Retrogressive Thaw Slump
High
Low
High
Low
Agashashok River
0 1 2 3 4 5 Miles
0 1 2 3 4 5 6 Kilometers



159°20'W
159°10'W
159°W
68°5'N
68°0'N
67°55'N
159°10'W
159°W
158°50'W
68°5'N
68°0'N
Anisak River
Noatak River
1
2
Okpik Lake
Lake Kangilipak
Terrain Suitability
Active Layer Detachment Slide
Both
Retrogressive Thaw Slump
High
Low
High
Low
0 1 2 3 4 5 Miles
0 1 2 3 4 5 6 Kilometers


161°40'W
161°30'W
161°20'W
67°45'N
67°40'N
67°35'N
Eli River
Agashashok River
Terrain Suitability
Active Layer Detachment Slide
Both
Retrogressive Thaw Slump
High
Low
High
Low
0 1 2 3 4 5 Miles
0 1 2 3 4 5 6 Kilometers


164°W
163°W
162°W
161°W
160°W
159°W
158°W
157°W
156°W
155°W
154°W
153°W
152°W
151°W
150°W
149°W
68°N
67°N
Toolik Field Station
Noatak
Kotzebue
ARCTIC OCEAN
Chukchi Sea
RUSSIA
Alaska (USA)
CANADA
Bering Sea
PACIFIC OCEAN
0 50 100 Miles
0 50 100 150 Kilometers
ALD Suitable Terrain by MAAT Range for Observed ALD Features, 1990-1999
above 1 SD of MAAT for Observed ALDs
within 1 SD of MAAT for Observed ALDs
below 1 SD of MAAT for Observed ALDs


164°W
163°W
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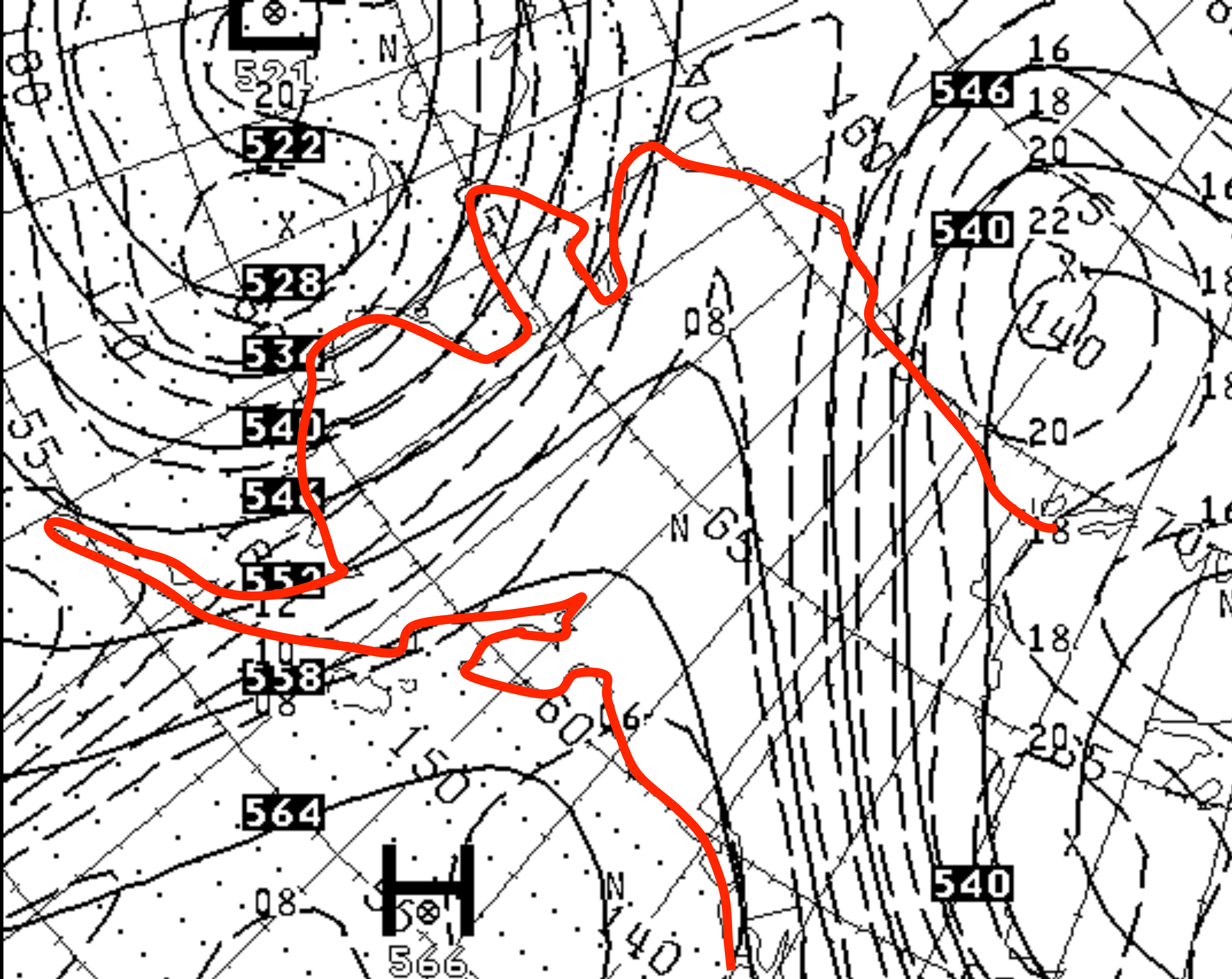
153°W
152°W
151°W
150°W
149°W
68°N
67°N
Toolik Field Station
Noatak
Kotzebue
ARCTIC OCEAN
Chukchi Sea
RUSSIA
Alaska (USA)
CANADA
Bering Sea
PACIFIC OCEAN
0 50 100 Miles
0 50 100 150 Kilometers
RTS Suitable Terrain by MAAT Range for Observed RTS Features, 1990-1999
above 1 SD of MAAT for Observed RTSs
within 1 SD of MAAT for Observed RTSs
below 1 SD of MAAT for Observed RTSs



522
528
534
540
546
552
558
564
H
566
546
540
540

Ecotype	% of Study Region	% of RTS Features	% Differential	% of ALD Features	% Differential
Alpine Dryas Dwarf Shrub	19.0	15.7	0.8	20.0	1.1
Alpine Ericaceous Dwarf Shrub	0.0	0.0	0.0	5.0	2.5
Alpine Ericaceous Dwarf Shrub	2.0	2.8	1.4	0.0	0.0
Alpine Wet Sedge Meadow	1.0	1.0	1.0	1.0	1.5
Lowland Birch-Ericaceous-Willow Low Shrub	3.0	2.4	0.8	0.0	0.0
Lowland Sedge Fen	1.0	2.8	2.8	0.0	0.0
Riverine Alder or Willow Tall Shrub	1.0	1.6	1.6	0.0	0.0
Riverine Birch-Willow Low Shrub	1.0	2.0	2.0	0.0	0.0
Riverine Wet Sedge Meadow	1.0	1.2	1.2	0.0	0.0
Riverine Willow Low Shrub	1.0	0.9	0.9	0.0	0.0
Upland Alder-Willow Tall Shrub	4.0	6.8	1.7	9.0	2.3
Upland Birch-Ericaceous-Willow Low Shrub	12.0	23.7	2.0	23.0	1.9
Upland Dwarf Birch-Tussock Shrub	19.0	19.2	1.0	29.0	1.5
Upland Sedge-Dryas Meadow	6.0	9.6	1.6	6.0	1.0
Upland White Spruce Forest	4.0	3.0	0.8	1.0	0.3
Upland Willow Low Shrub	0.0	0.0	0.0	3.0	1.5
Upland Willow Low Shrub	2.0	2.9	1.4	0.0	0.0

Surficial Geology	% of Study Region	% of RTS Features	% Differential	% of ALD Features	% Differential
Alluvium	6.1	7.0	1.1	1.0	0.2
Thin Soil over Near-surface Bedrock	53.8	26.0	0.5	54.0	1.0
Colluvium	6.9	7.0	1.0	20.0	2.9
Glacial Drift	**16.4**	**46.0**	**2.8**	22.0	1.3
Fan Deposits	1.8	0.3	0.2	0.2	0.1
Gravel	0.1	0.1	0.7	0.0	0.0
Ice Contact	0.5	1.0	2.1	0.0	0.1
Inwash / Outwash	1.5	0.4	0.3	0.1	0.1
Lacustrine / Glaciolacustrine	9.4	11.0	1.2	2.0	0.2
Organic	0.0	0.0	0.0	0.0	0.0
Other (Active Glacier / Snowfield)	0.7	0.0	0.0	0.5	0.7
Sand	0.6	0.2	0.3	0.0	0.0
Silt	1.0	0.0	0.0	0.0	0.0
Terrace	1.2	1.0	0.8	0.0	0.0

Lithology	% of Study Region	% of RTS Features	% Differential	% of ALD Features	% Differential
Noncarbonate	89.8	99.2	1.1	98.3	1.1
Carbonate	10.2	0.8	0.1	1.7	0.2

Approach

Determine year of initiation for active RTS features

archive of SAR imagery

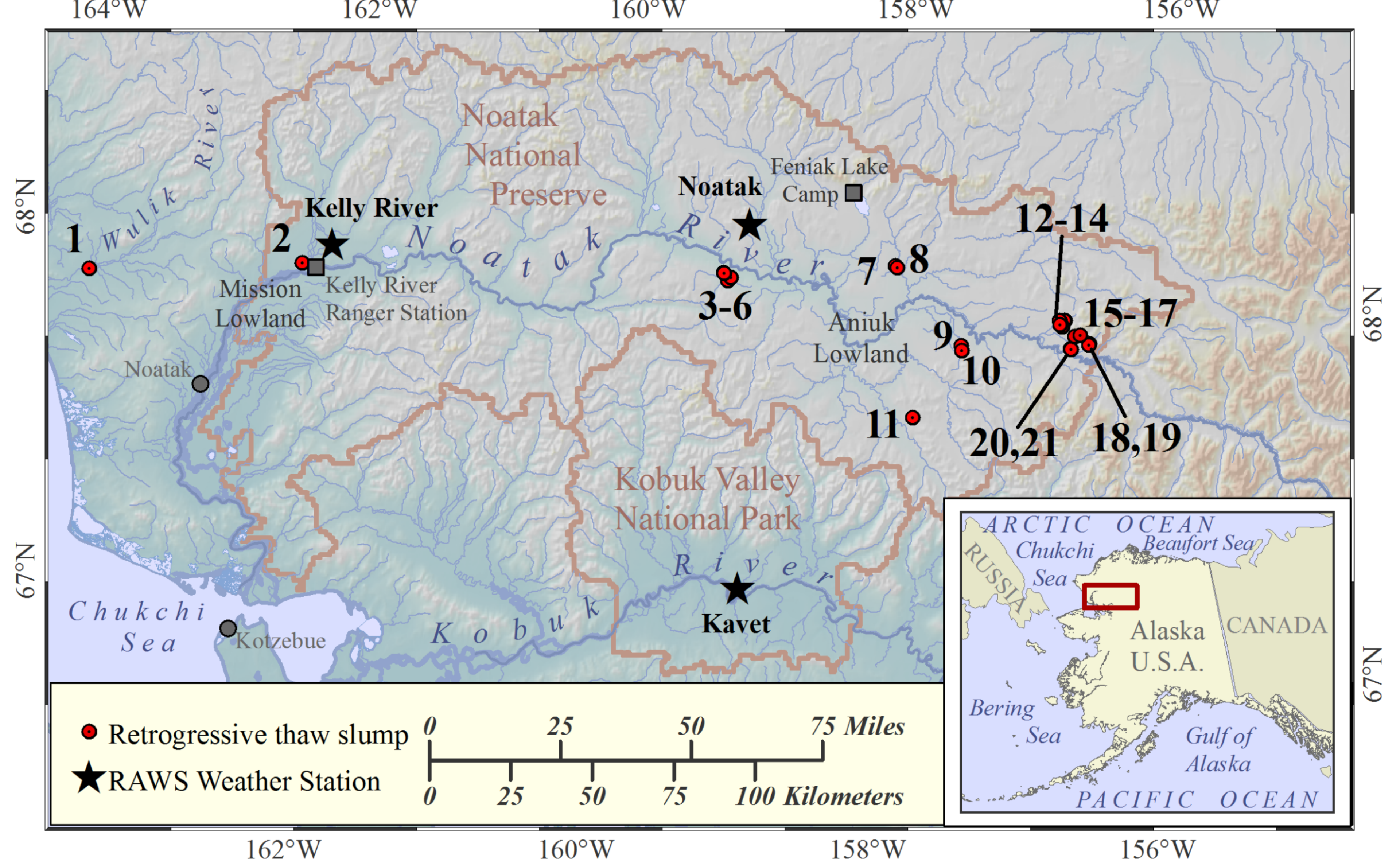
(ERS 1&2, 1997-2010, ~bi-weekly)

Examine initiation timing against:

weather patterns and events

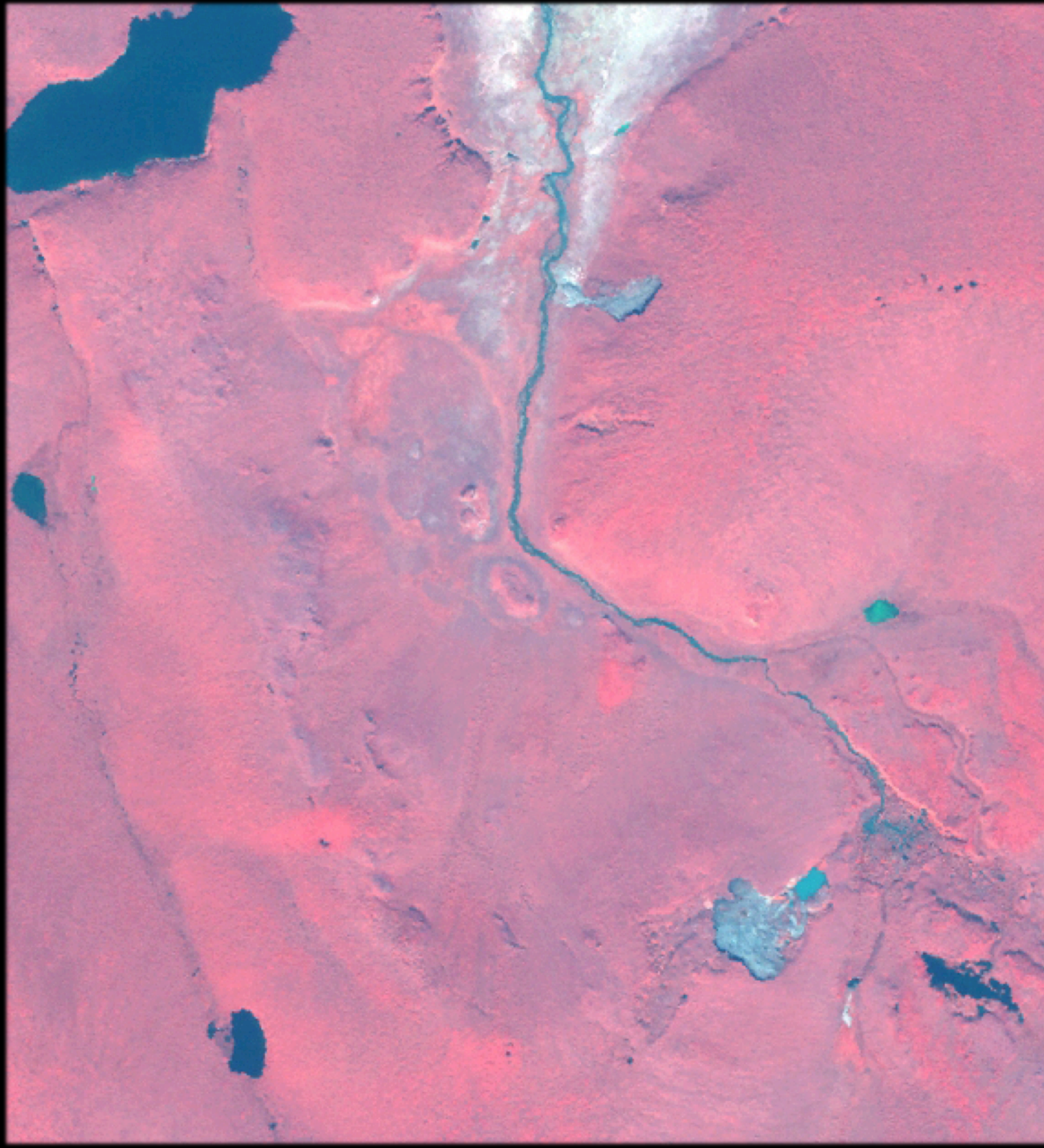
seasonal snowpack coverage and duration

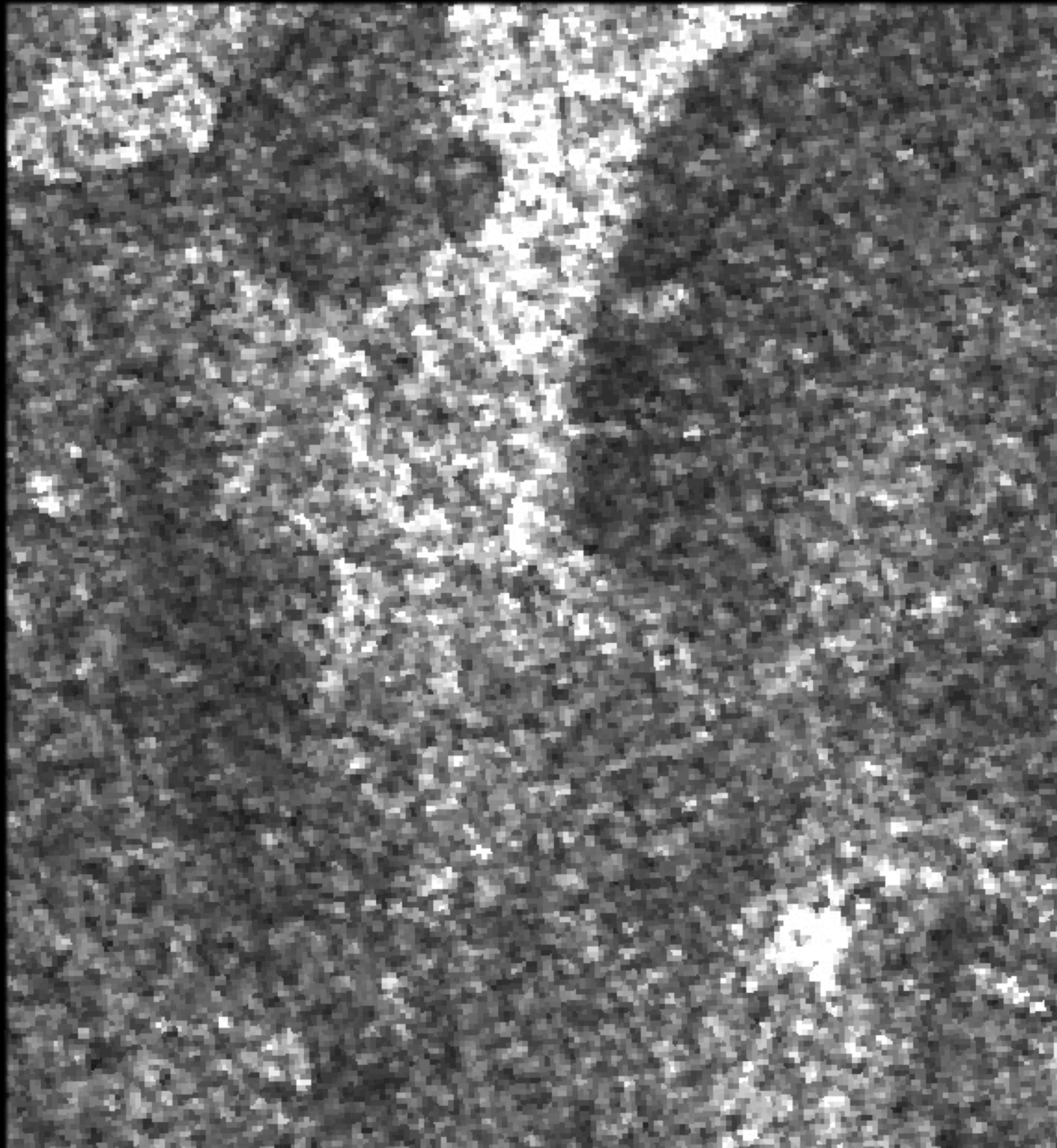
wildfire occurrence



21 features chosen for study:

a) Actively degrading
b) Big enough for reliable detection in imagery
c) Not along river bank cuts





A) 2008 hi-res image

B) 2002 Landsat ETM

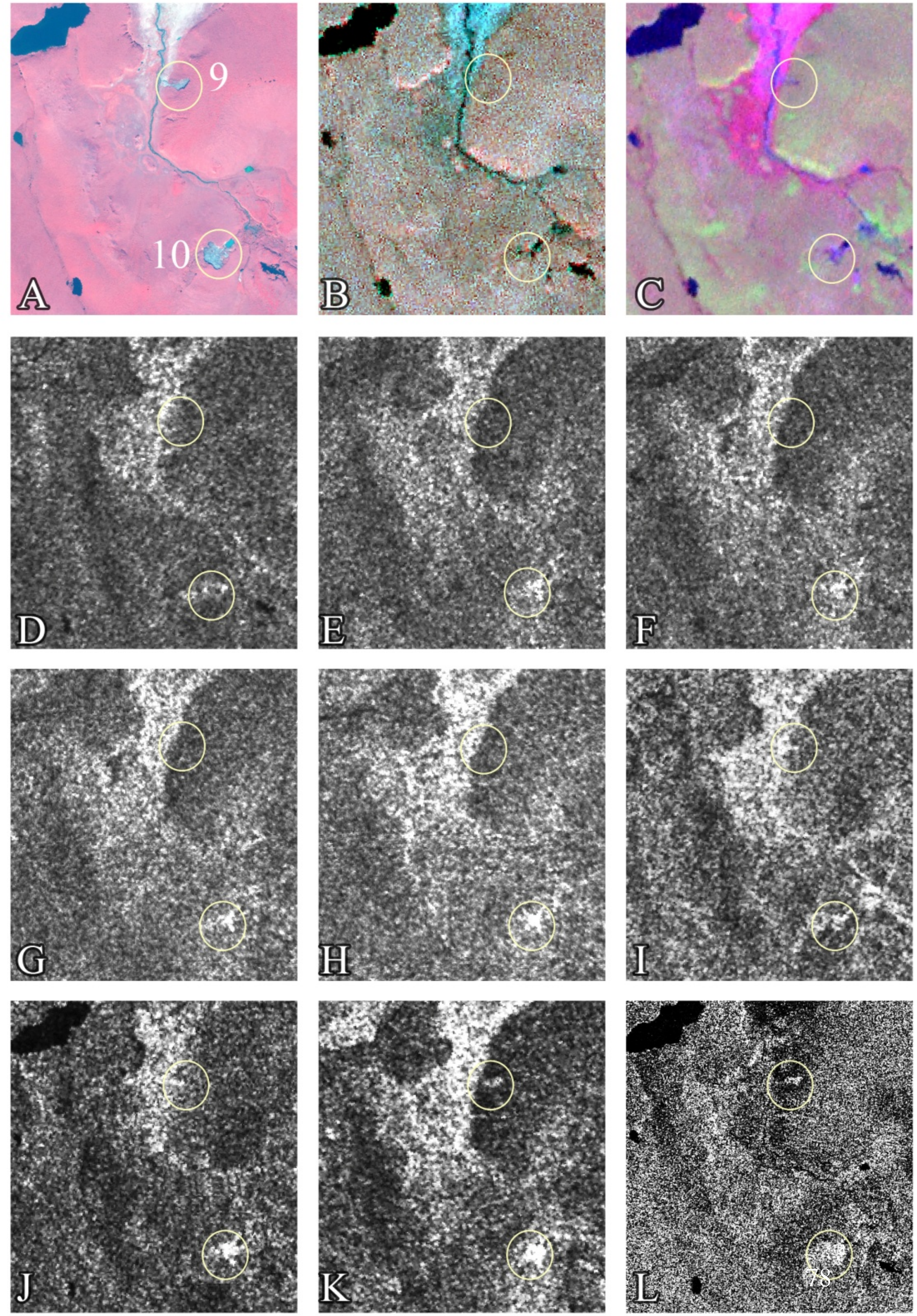
C) 2005 Landsat ETM+

D – L) SAR Imagery

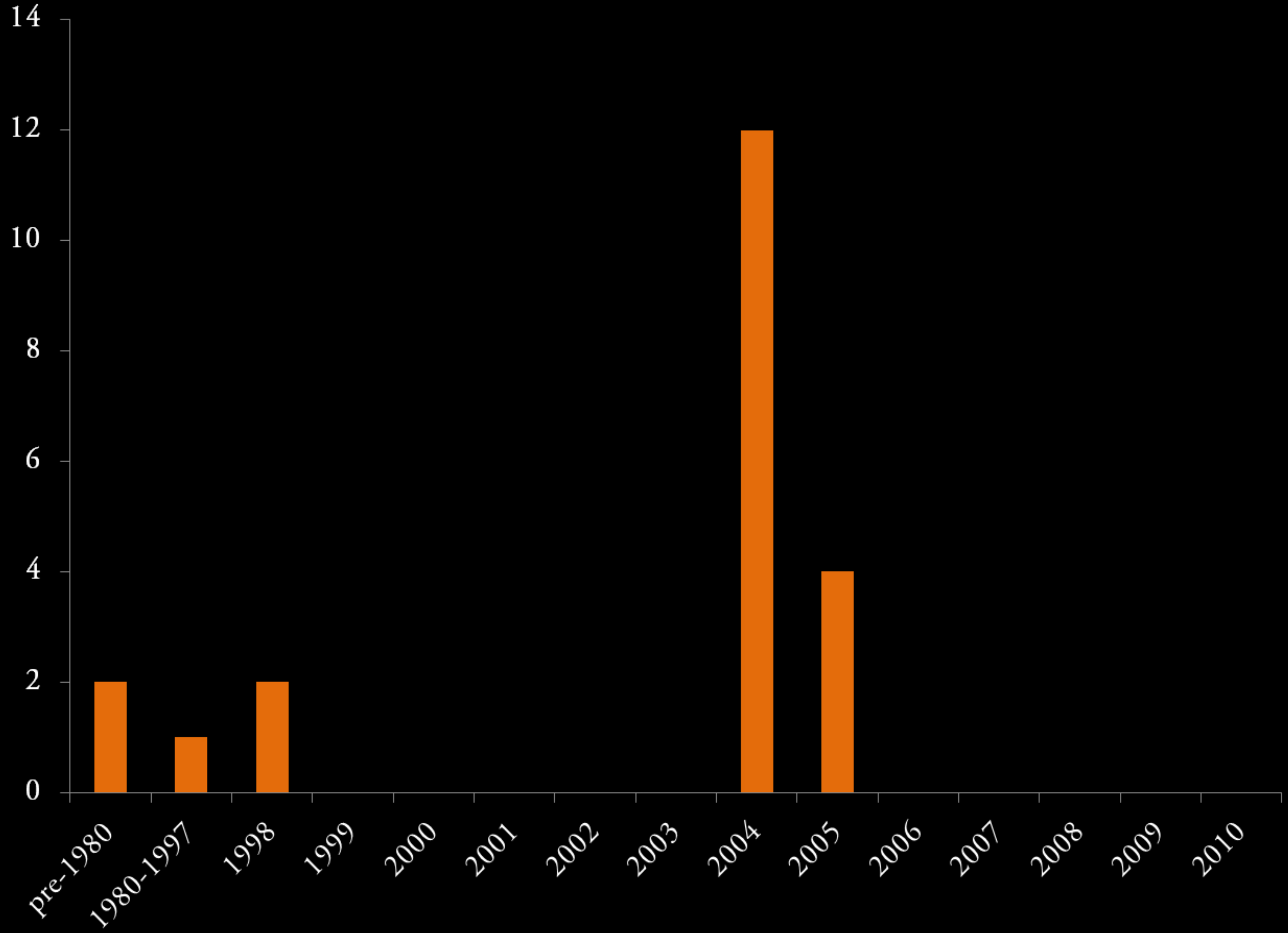
1997-2009

RTS 10 initiated in 1998

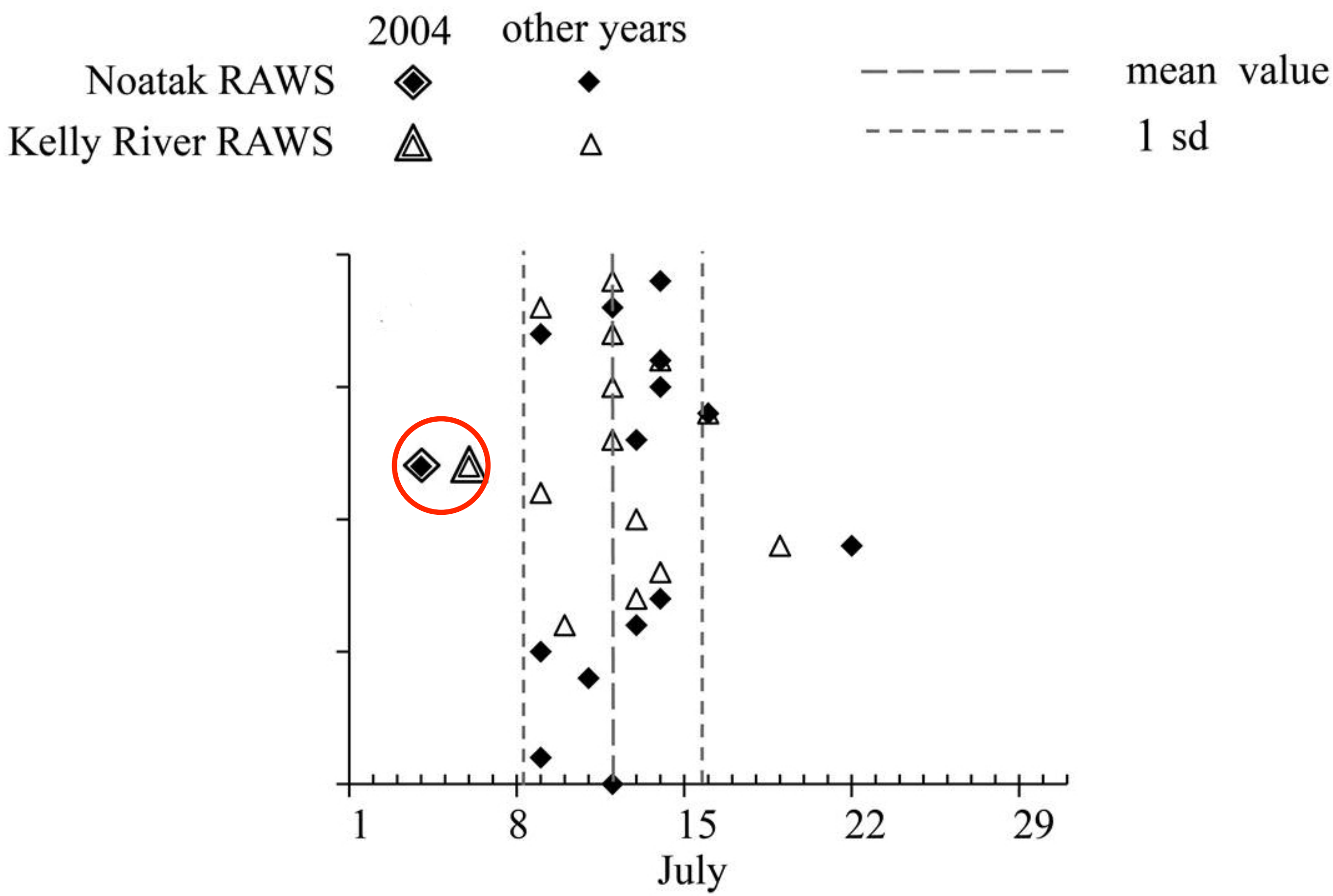
RTS 9 initiated in 2004

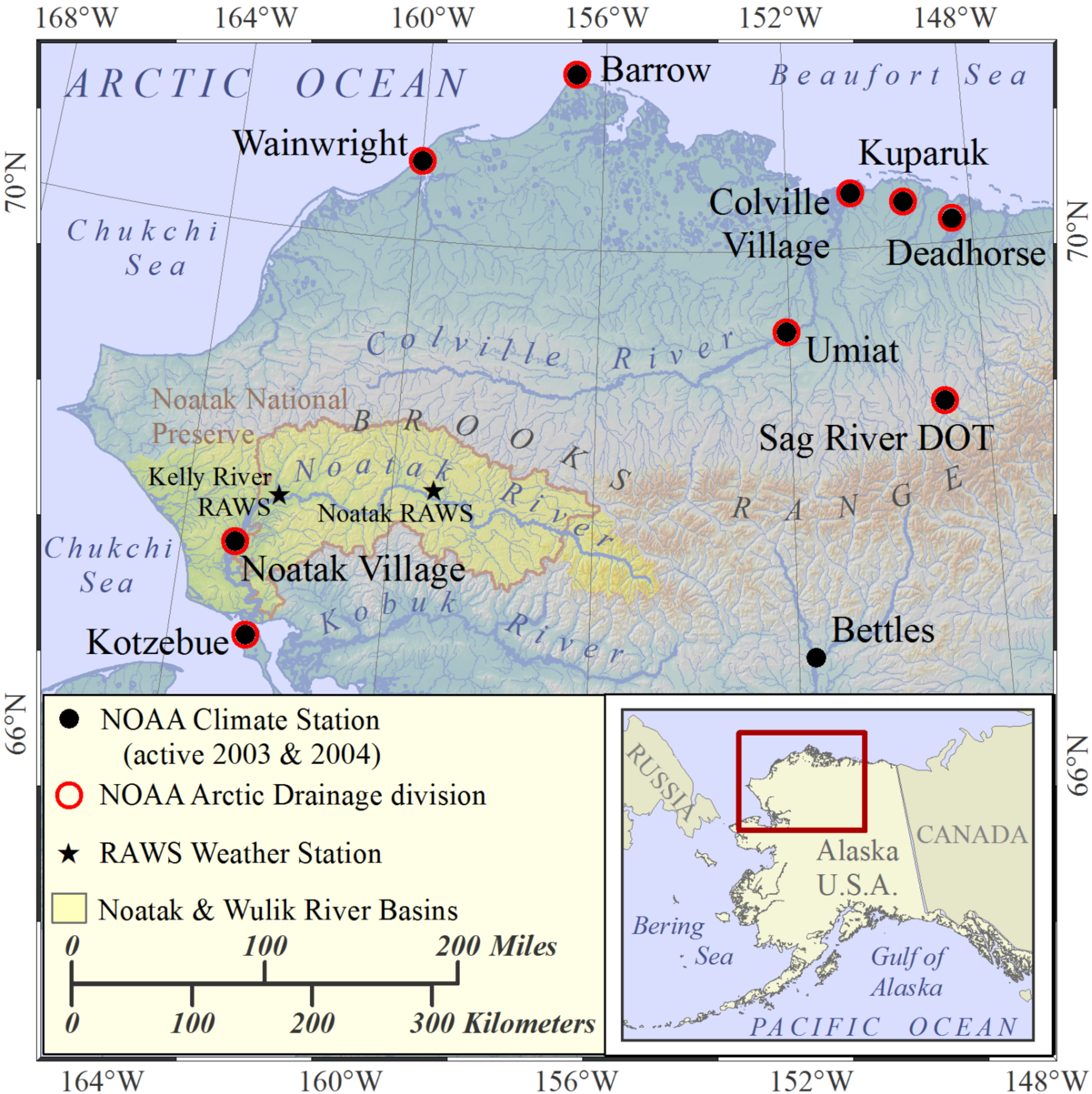


Retrogressive Thaw Slump Initial Detection Dates



Median date of thawing index, 1992 - 2012




168°W
164°W
160°W
156°W
152°W
148°W
ARCTIC OCEAN
Barrow
Beaufort Sea
Wainwright
Kuparuk
Colville Village
Deadhorse
70°N
Chukchi Sea
Colville River
Umiat
Noatak National Preserve
BROOKS RANGE
Sag River DOT
Kelly River RAWS
Noatak River
Noatak RAWS
Chukchi Sea
Noatak Village
Kobuk River
Kotzebue
Bettles
66°N
NOAA Climate Station (active 2003 & 2004)
NOAA Arctic Drainage division
RAWS Weather Station
Noatak & Wulik River Basins
0 100 200 Miles
0 100 200 300 Kilometers
RUSSIA
CANADA
Alaska U.S.A.
Bering Sea
Gulf of Alaska
PACIFIC OCEAN
164°W
160°W
156°W
152°W
148°W

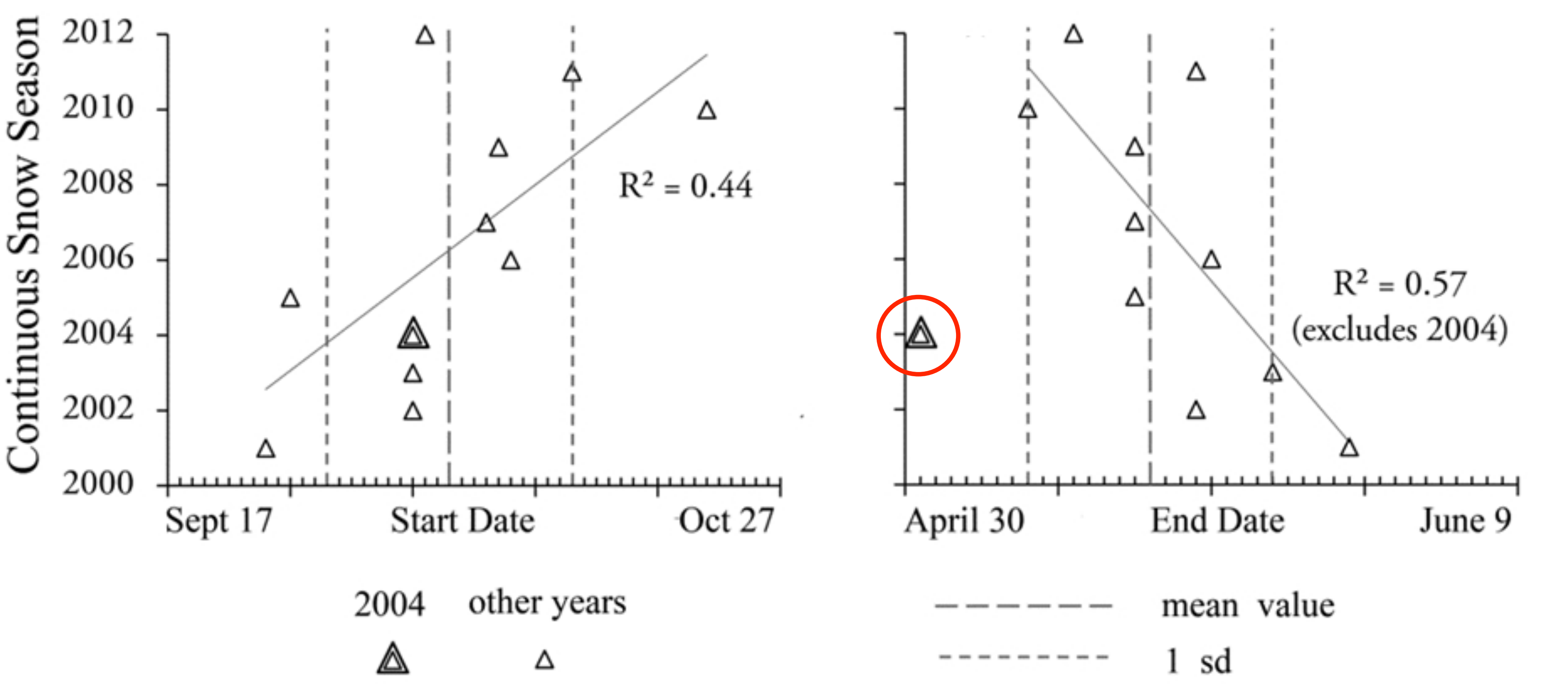
May 2004 precipitation at the NOAA and RAWS stations

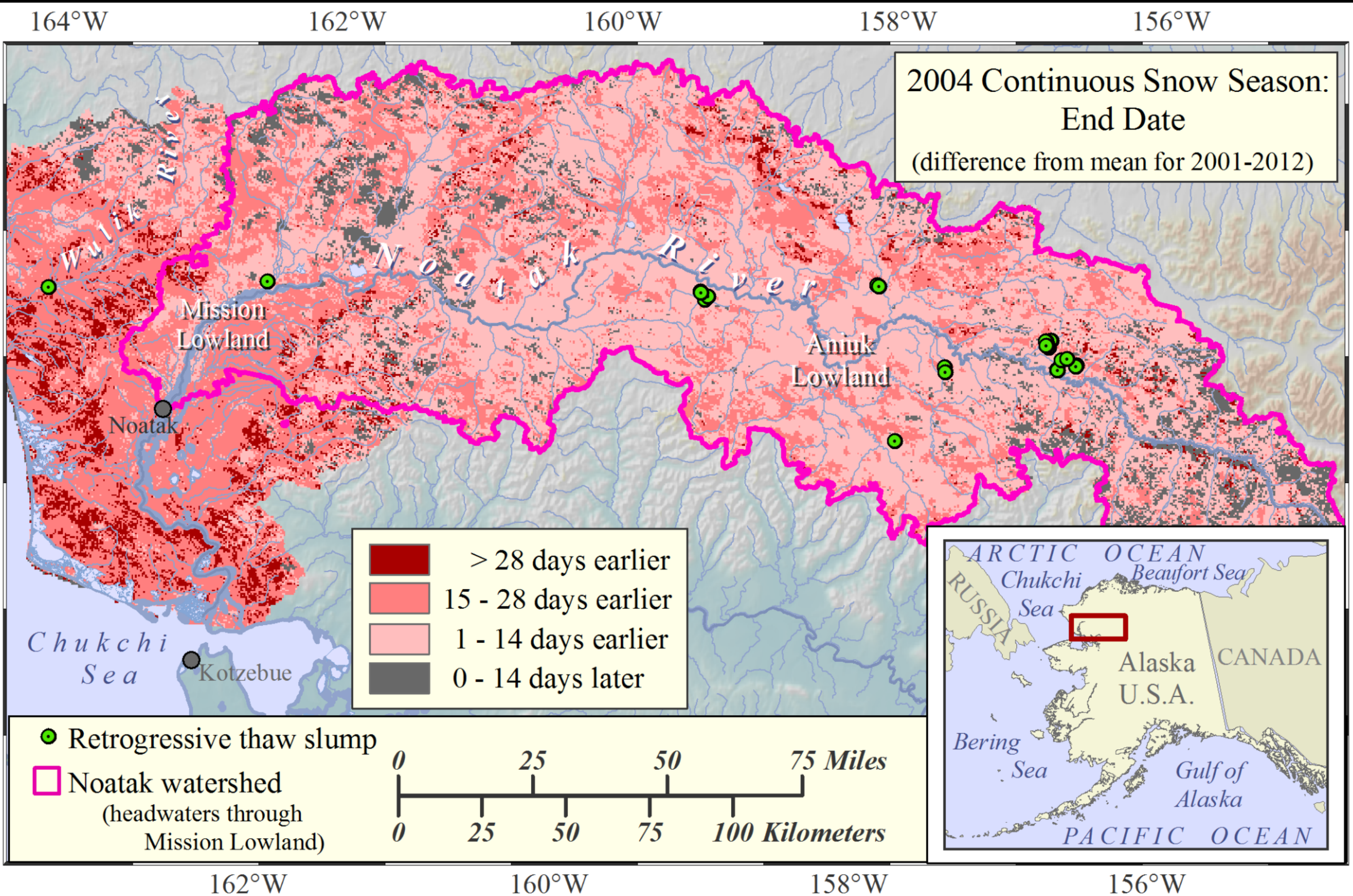
+ includes record rainfall

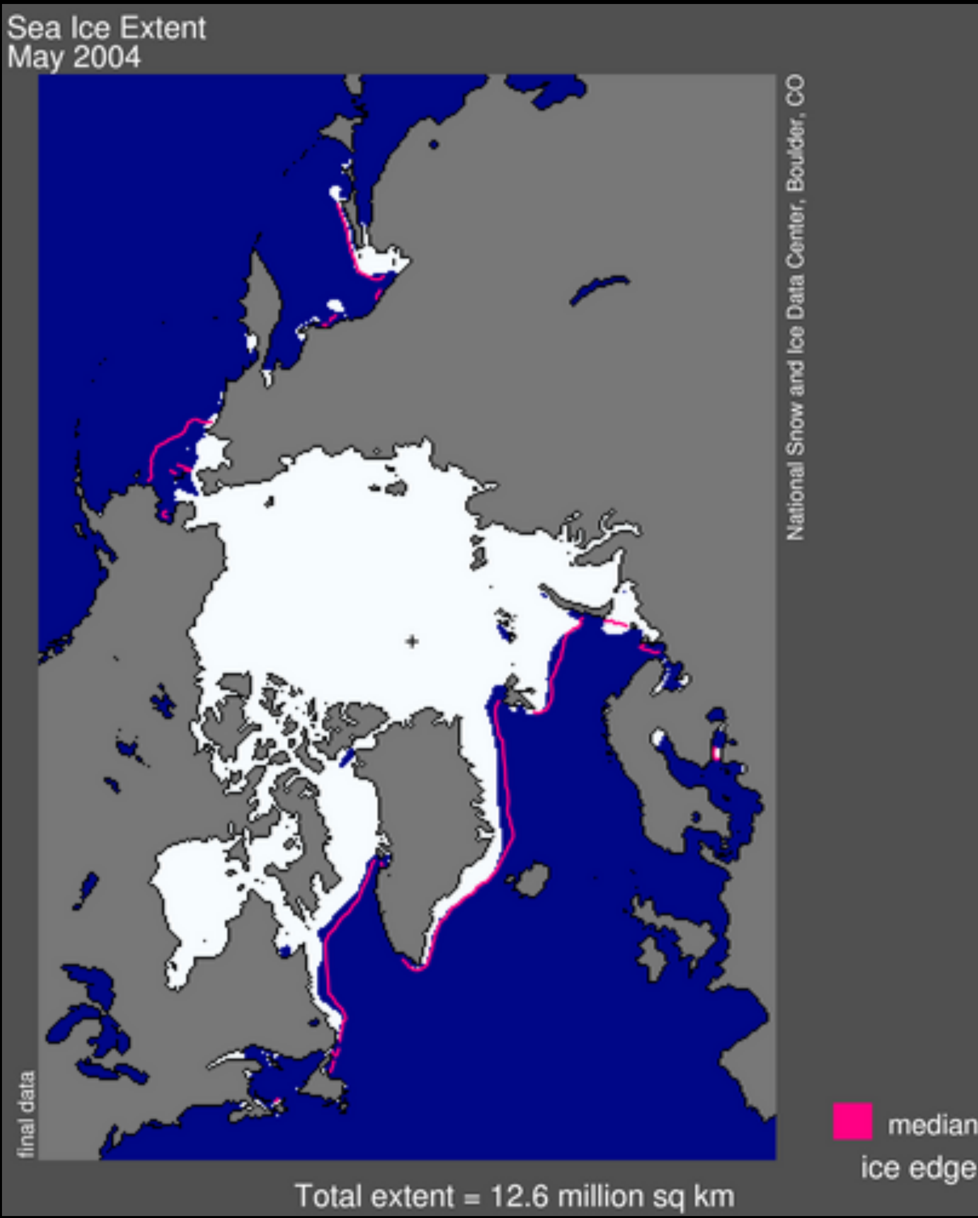
	5/6 to 5/11 cm	5/22 to 5/24 cm	May 2004 total cm
Kotzebue NOAA	2.2	0.58	3.5 +
Kelly River RAWS	3.9	2.8	8.1
Noatak Village NOAA	3.5	1.8	6.9
Noatak RAWS	N/A	N/A	N/A
Bettles NOAA	1.2	0.2	4.2

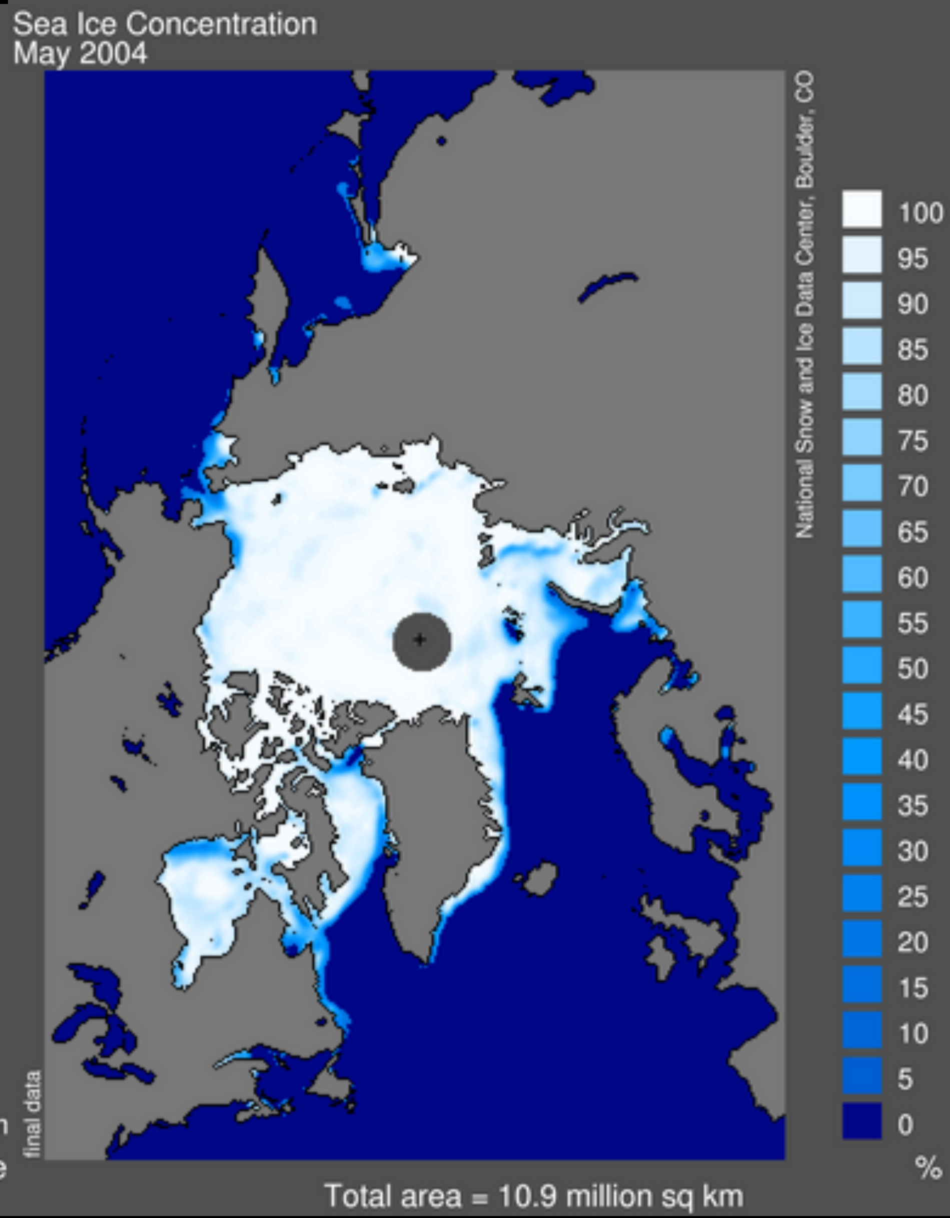
Continuous Snow Season in the Noatak Basin

(from MODIS Snow Metrics 2001-2012)




2004 Continuous Snow Season: End Date
(difference from mean for 2001-2012)
164°W
162°W
160°W
158°W
156°W
68°N
67°N
Wulik River
Noatak River
Mission Lowland
Aniuk Lowland
Noatak
Kotzebue
Chukchi Sea
> 28 days earlier
15 - 28 days earlier
1 - 14 days earlier
0 - 14 days later
Retrogressive thaw slump
Noatak watershed
(headwaters through Mission Lowland)
0 25 50 75 Miles
0 25 50 75 100 Kilometers
ARCTIC OCEAN
Chukchi Sea
Beaufort Sea
RUSSIA
Alaska U.S.A.
CANADA
Bering Sea
Gulf of Alaska
PACIFIC OCEAN





http://nsidc.org/data/seaice_index/

Anomalous weather early in the thaw season:

- Sun angles are highest
- Duration of daylight is longest
- Cloud cover is minimal (typically)
- Before bud burst (mostly)

- Increased incident solar radiation to the surface
- Accelerated thaw front advance – with the rest of the thaw season still to come

Summary

- RTS features initiate in clusters (temporally)
- Timing of weather may be critical
- Early exposure likely accelerates thaw front advance

Take Home

- Response trajectories may critically depend on the timing of weather patterns and events.
- Correctly forecasting future impacts and feedbacks hinges on matching responses with future change scenarios.

Approach

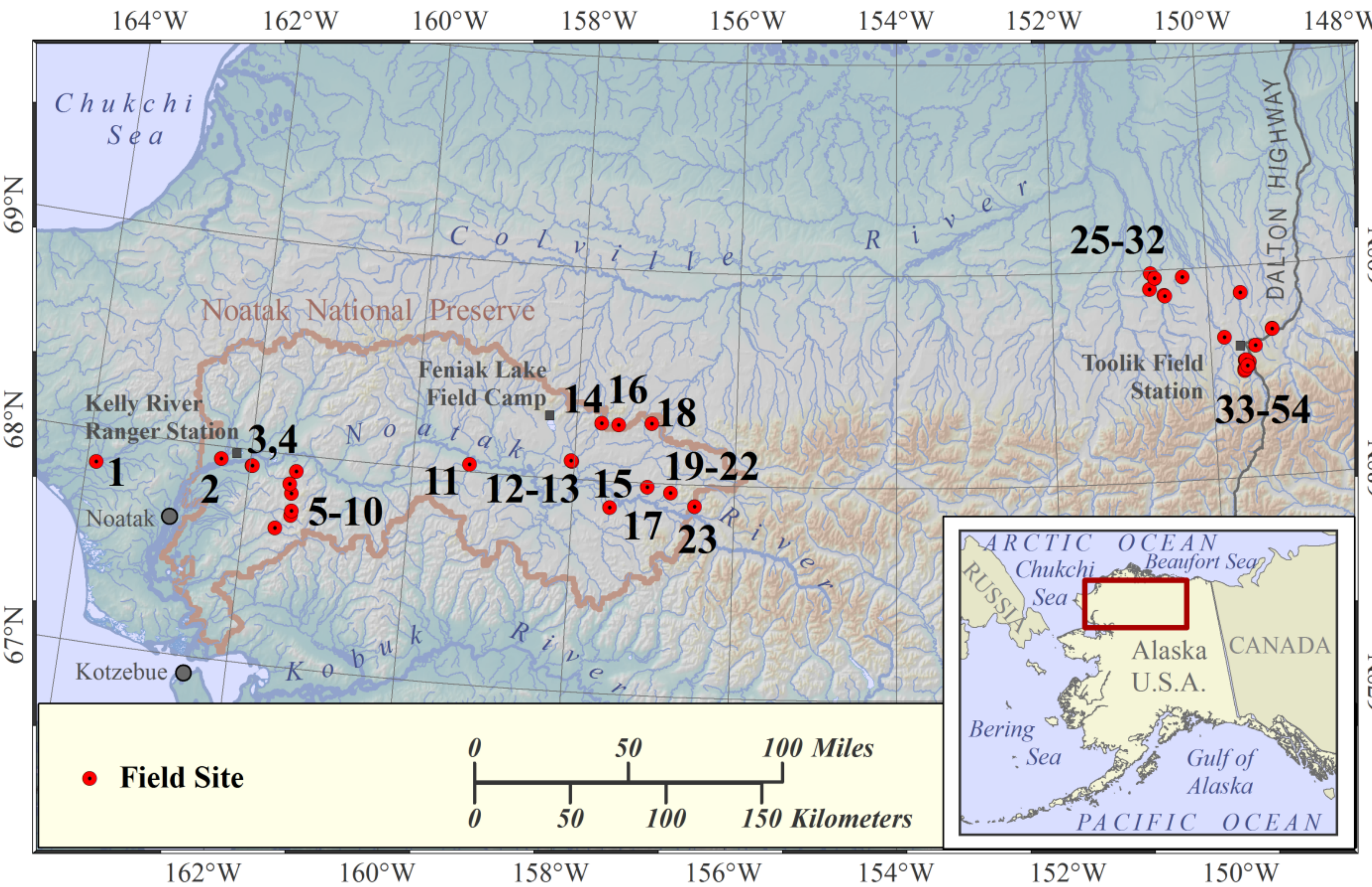
Examine terrain and upper permafrost properties (field)

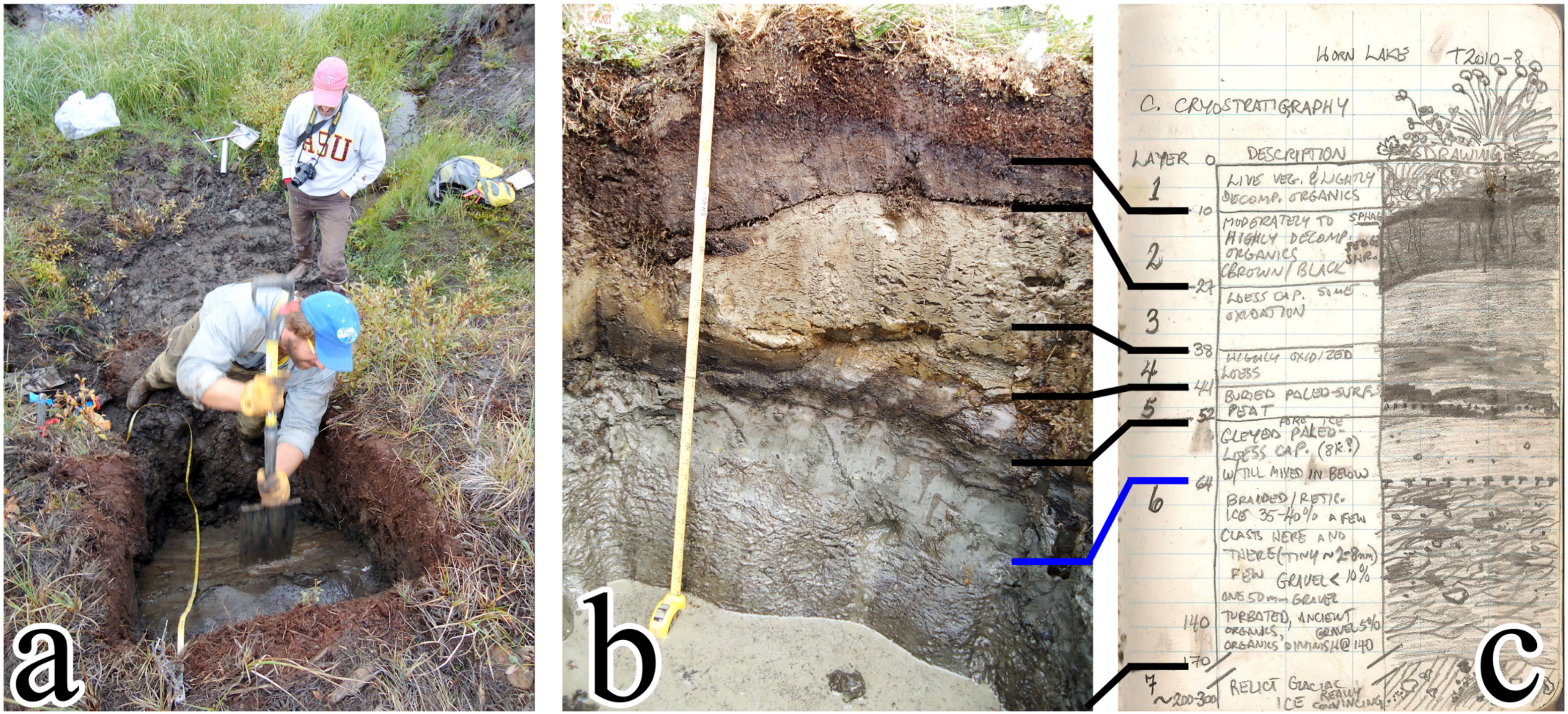
Cryostructures	Vegetation Class
Ground Ice %	Parent Material
Contemporary Soil	Organic Layer
Active Layer Depth	Microtopography

Examine (dis)similarity among sites using:

Multiple Factor Analysis (MFA) ordination

Hierarchical Clustering


164°W
162°W
160°W
158°W
156°W
154°W
152°W
150°W
148°W
69°N
68°N
67°N
Chukchi Sea
Colville River
Noatak National Preserve
Feniak Lake Field Camp
Kelly River Ranger Station
Noatak River
Noatak
Kotzebue
Kobuk River
DALTON HIGHWAY
Toolik Field Station
1
2
3,4
5-10
11
12-13
14
15
16
17
18
19-22
23
25-32
33-54
Field Site
0 50 100 Miles
0 50 100 150 Kilometers
ARCTIC OCEAN
Chukchi Sea
Beaufort Sea
RUSSIA
Alaska U.S.A.
CANADA
Bering Sea
Gulf of Alaska
PACIFIC OCEAN


a
b
c
HORN LAKE T2010-8
C. CRYOSTRATIGRAPHY
LAYER
DESCRIPTION
DRAWING
0
1
LIVE VEG. & LIGHTLY DECOMP. ORGANICS
10
2
MODERATELY TO HIGHLY DECOMP. ORGANICS (BROWN/BLACK
27
3
LOESS CAP. SOME OXIDATION
38
4
HIGHLY OXIDIZED LOESS
44
5
BURIED PALEO-SURF. PEAT
52
GLEYED PALEO-LOESS CAP. (8K?)
W/TILL MIXED IN BELOW
64
6
BRAIDED/RETIC. ICE 35-40% A FEW CLASTS HERE AND THERE (TINY ~2-8mm)
FEW GRAVEL < 10%
ONE 50mm GRAVEL
140
TURBATED, ANCIENT ORGANICS, GRAVEL 5%
ORGANICS DIMINISH @ 140
170
7
~200-300
RELICT GLACIAL ICE
REALLY CONVINCING

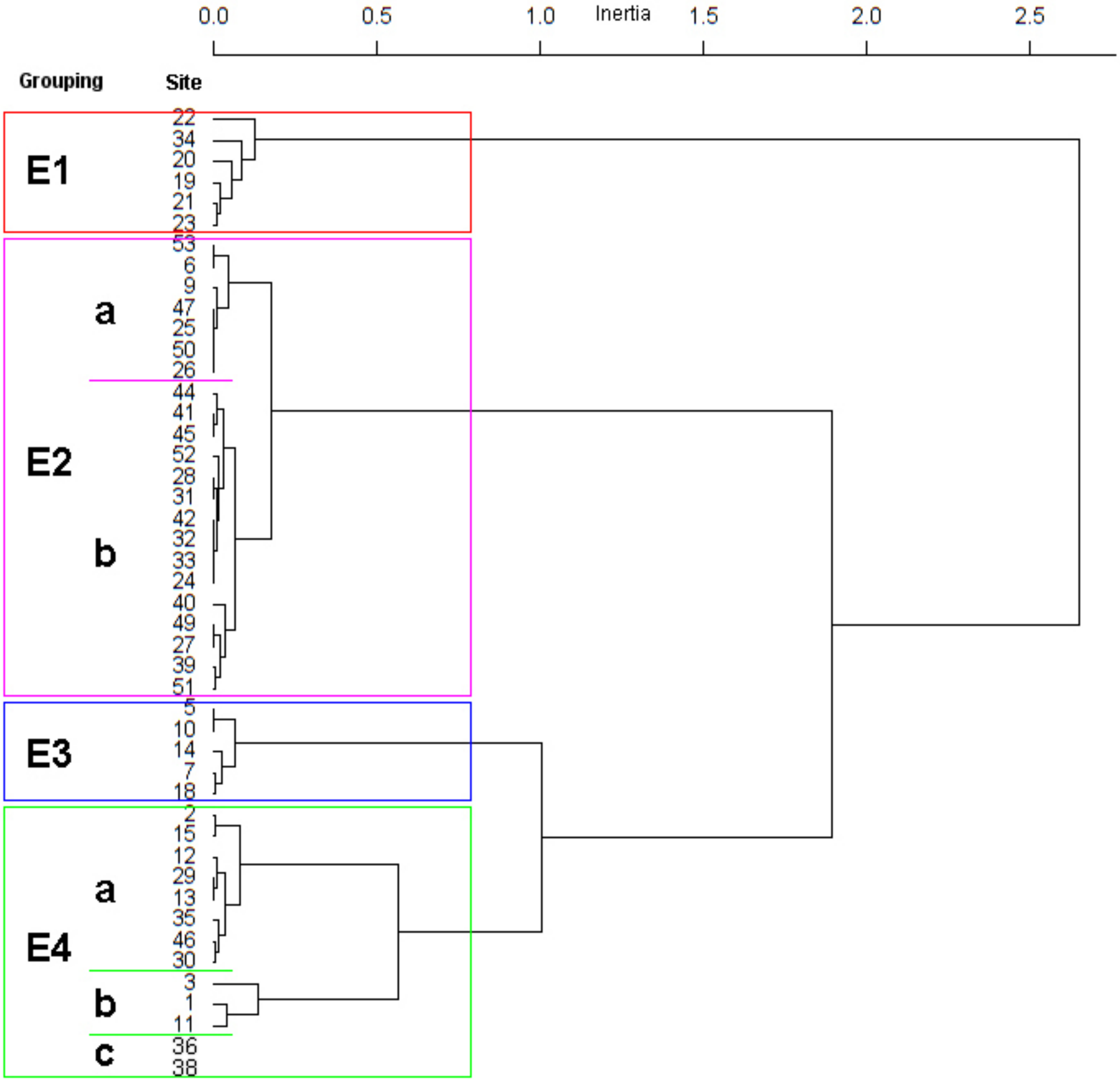
Methods

MFA Ordination:

Organize variables into logical blocks:

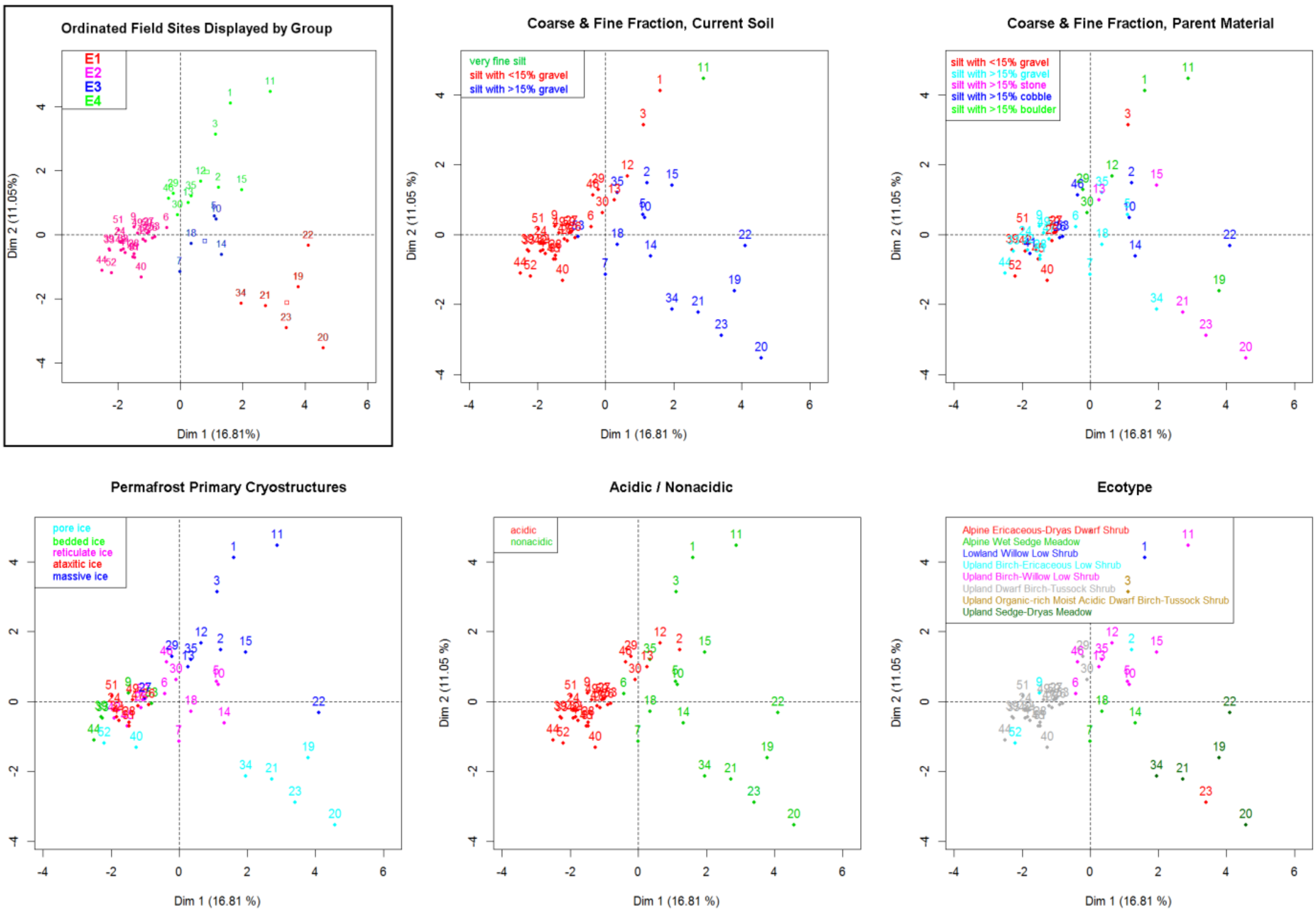
- Vegetative
- Substrate
- Ground Ice

Each block is weighted evenly – no block dominates the ordination.

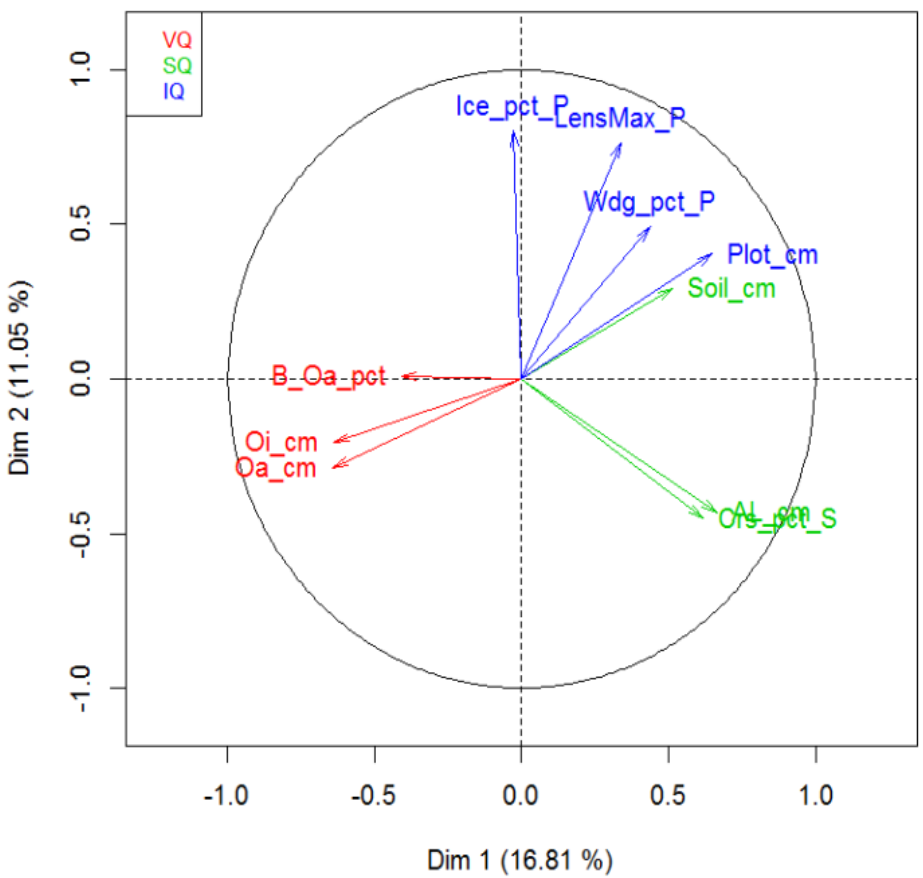


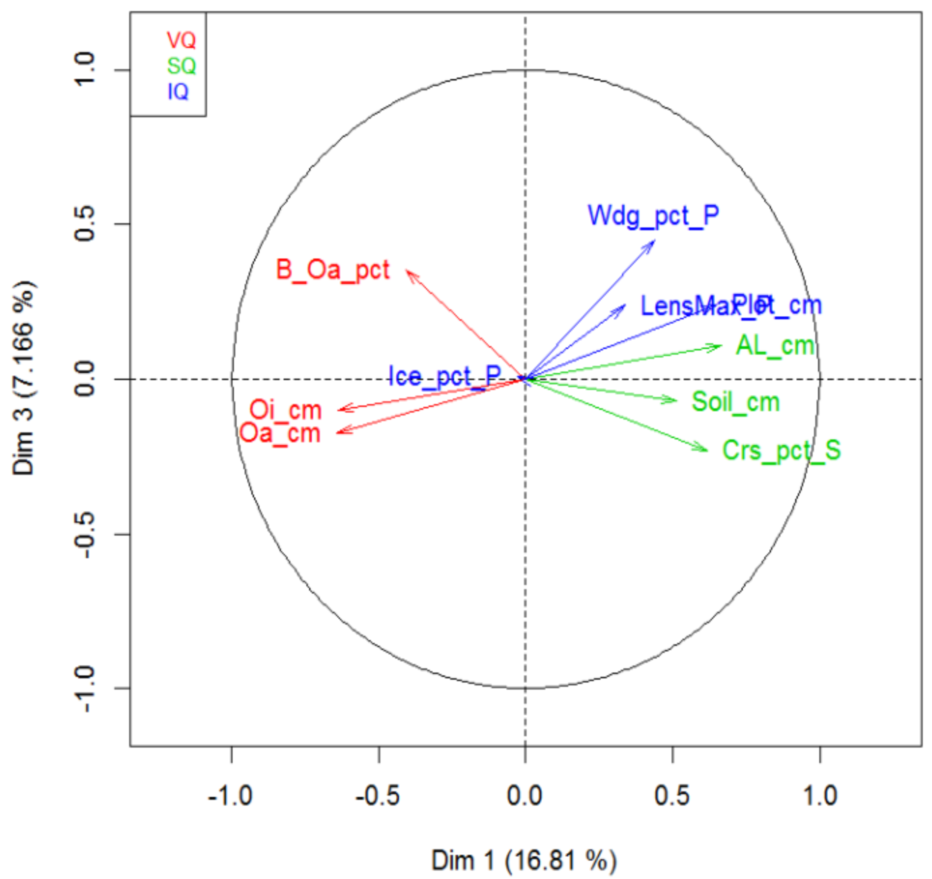
MFA: Hierarchical Clustering

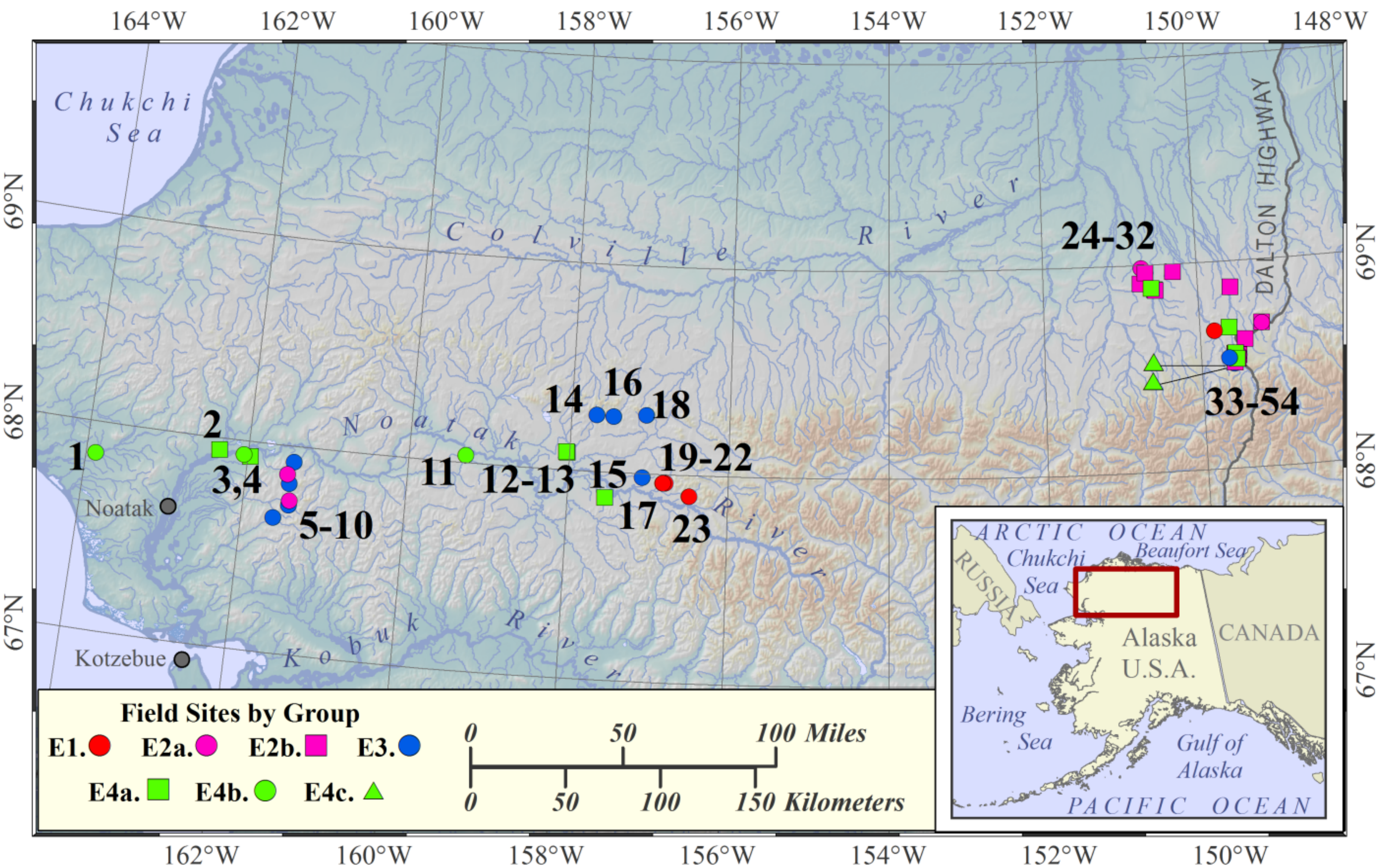
MFA: Factor Overlays



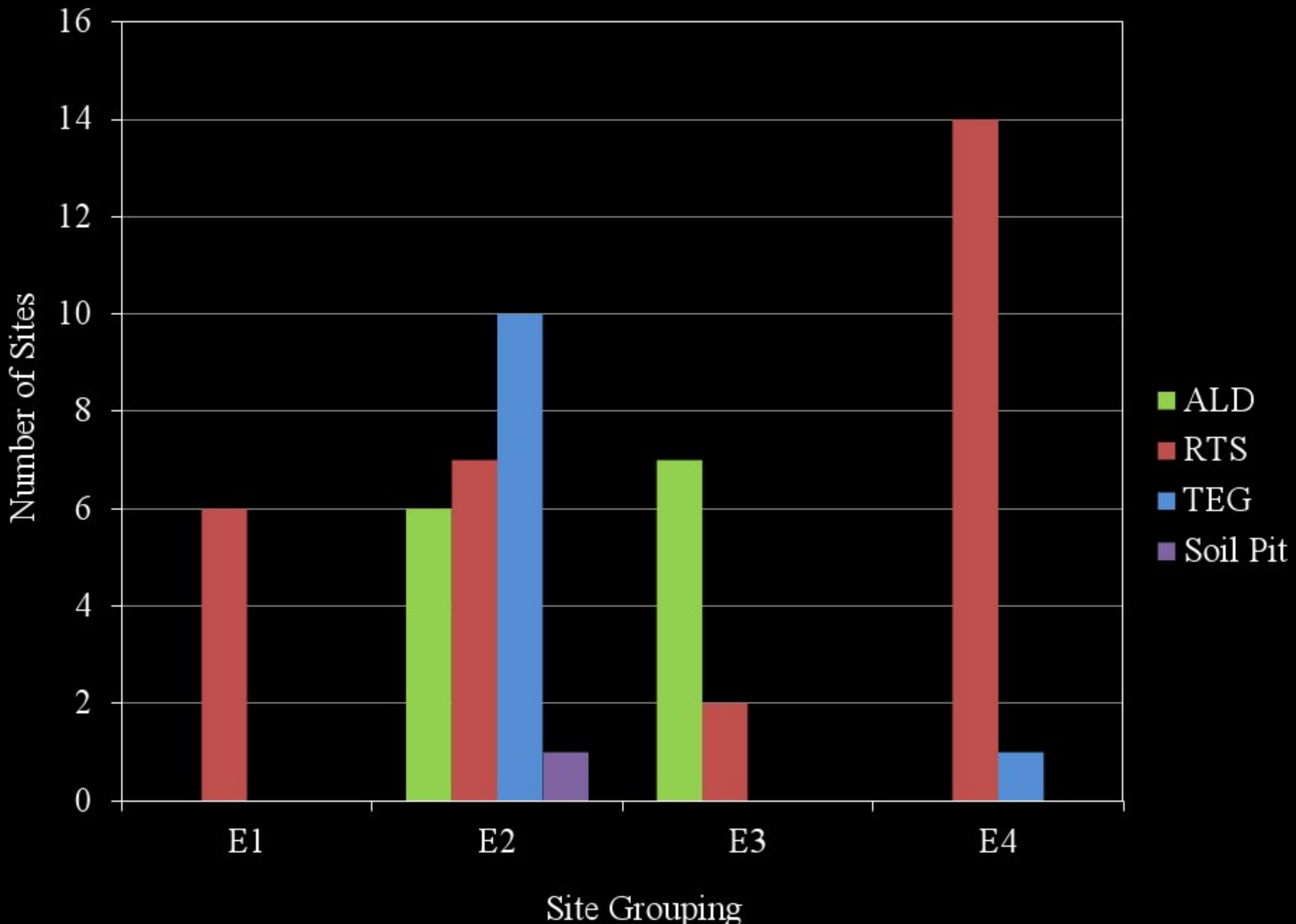
MFA: Influence of Blocks by Axis







164°W
162°W
160°W
158°W
156°W
154°W
152°W
150°W
148°W
69°N
68°N
67°N
Chukchi Sea
Colville River
DALTON HIGHWAY
24-32
33-54
Noatak River
14
16
18
1
2
3,4
5-10
11
12-13
15
17
19-22
23
Noatak
Kotzebue
Kobuk River
Field Sites by Group
E1.
E2a.
E2b.
E3.
E4a.
E4b.
E4c.
0 50 100 Miles
0 50 100 150 Kilometers
ARCTIC OCEAN
Beaufort Sea
Chukchi Sea
RUSSIA
Alaska U.S.A.
CANADA
Bering Sea
Gulf of Alaska
PACIFIC OCEAN


16
14
12
10
8
6
4
2
0
Number of Sites
E1
E2
E3
E4
Site Grouping
ALD
RTS
TEG
Soil Pit

Summary

- Terrain and permafrost properties are correlated across diverse landscapes in the study region
- Sites fall into consistent groupings
- Groupings correlate with permafrost degradation mode

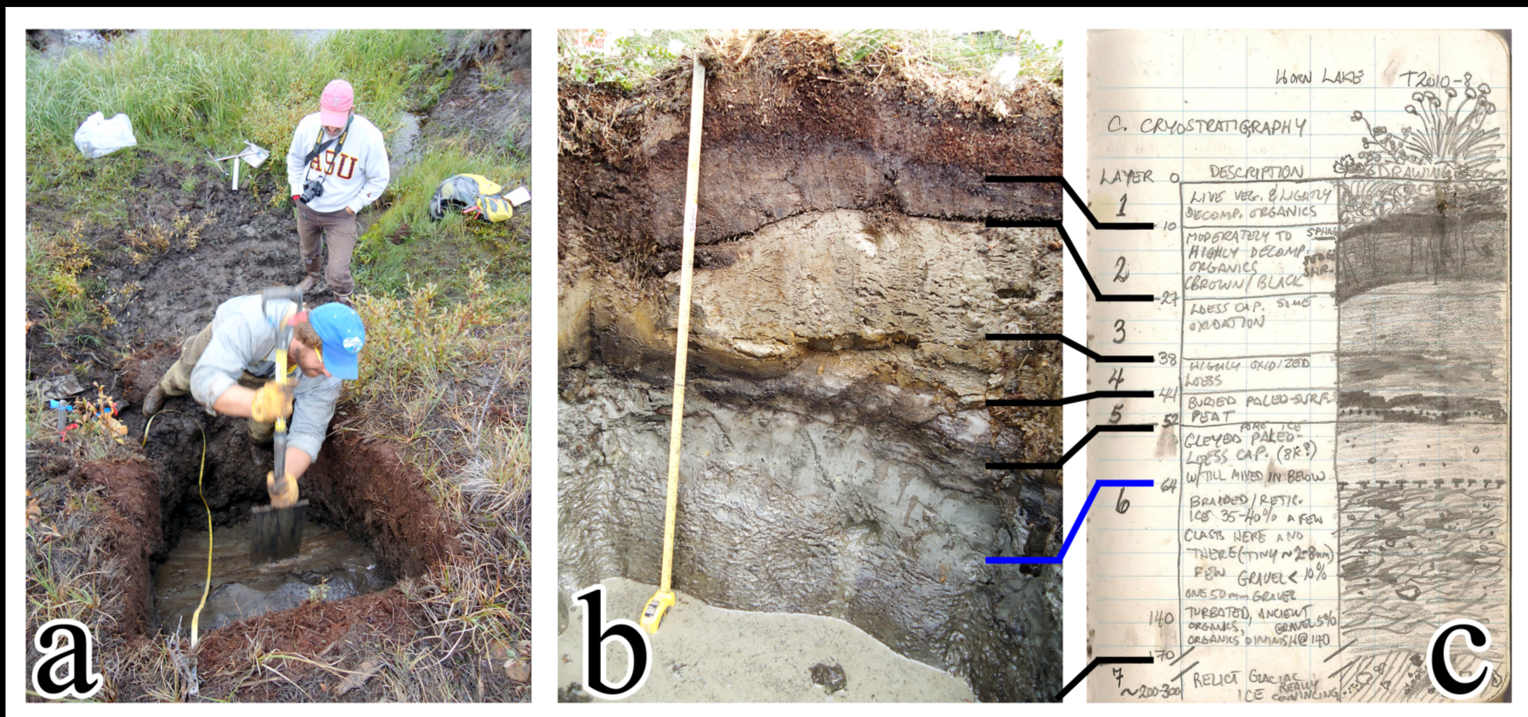
Take Home

- Relationships among terrain and permafrost properties may be used to estimate ALD and RTS terrain suitability at a regional scale.
- Regional estimates of ground ice properties may also be attainable, but the data aren’t there yet for this region.

TIMING OF RETROGRESSIVE THAW SLUMP INITIATION IN THE NOATAK BASIN, NORTHWEST ALASKA

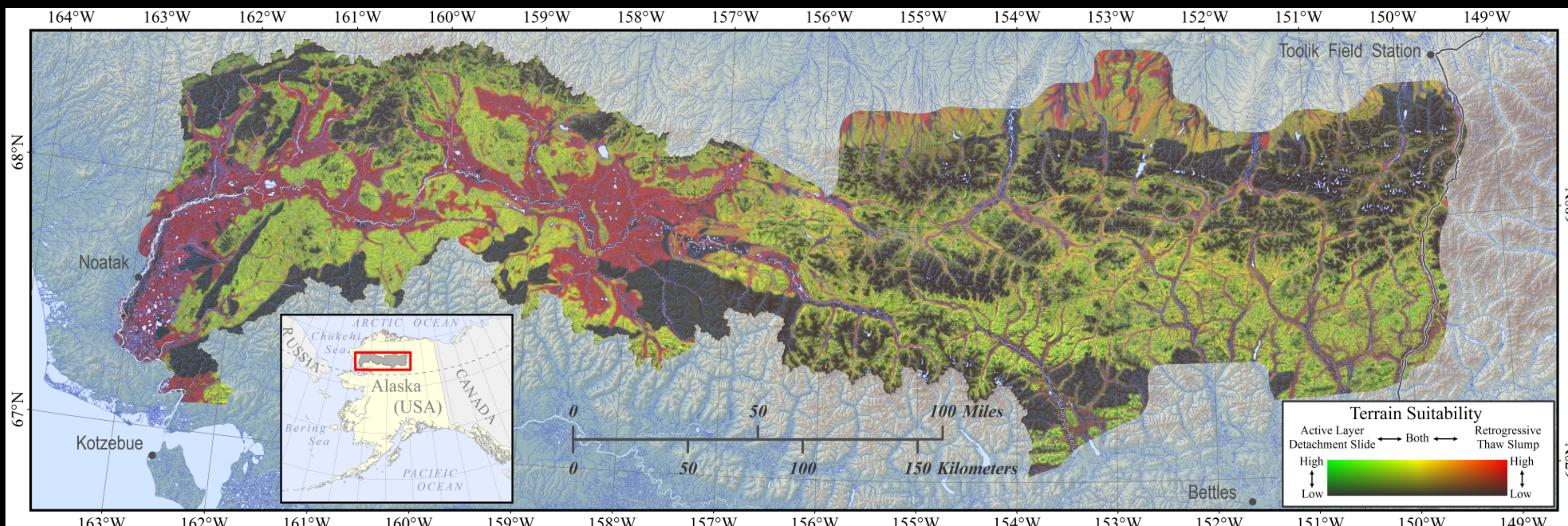
Balser, A. W., J. B. Jones, and R. Gens (2014), Timing of Retrogressive Thaw Slump Initiation in the Noatak Basin, Northwest Alaska, USA, *Journal of Geophysical Research: Earth Surface, 2013JF002889, doi: 10.1002/2013JF002889*

RELATIONSHIP OF TERRAIN AND PERMAFROST PROPERTIES IN THE BROOKS RANGE AND FOOTHILLS OF NORTHERN ALASKA



Balser, A. W., J. B. Jones, and M.T. Jorgenson. Prepared for submission to *Journal of Geophysical Research: Earth Surface.*

TERRAIN SUITABILITY FOR ALD AND RTS IN THE BROOKS RANGE AND FOOTHILLS OF NORTHWEST ALASKA



Balser, A. W., J. B. Jones, and M.T. Jorgenson. Prepared for submission to *Journal of Geophysical Research: Earth Surface.*