Complex Structures in Arctic Sea Ice and a Note on Walgreen Coast, Antarctica

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Recent Rapid Changes of the Cryosphere

- Glaciers in most mountain ranges retreat
- Antarctic and Greenland Ice Sheets lose elevation
- Outlet glaciers of ice sheets accelerate and retreat
- Northern Antarctic ice shelves break up
- Arctic sea-ice cover reaches record lows in coverage

Approach

Understanding Environmental Change through Geomathematical Analysis of Remote-Sensing Data

Objectives

Glaciologic objective:

Detect and quantify different forms of change in the cryosphere and attribute changes to glaciologic or sea-ice-morphogenetic processes

Remote-sensing objective:

Present and analyze observations from new instruments with a focus on the role of ICESat GLAS data

Geomathematical objective:

– Realize new methodological components for spatial structure analysis

– Identify, characterize and classify forms from hidden information in

(a) Undersampled situations

(b) Oversampled situations

Measurement objective:

Development of instrumentation to survey micro-topography and roughness of ice surfaces

(1) Glacier Roughness Sensor (GRS)

(2) UAV Laser Profilometer

(UAV- Unmanned Aerial Vehicle)

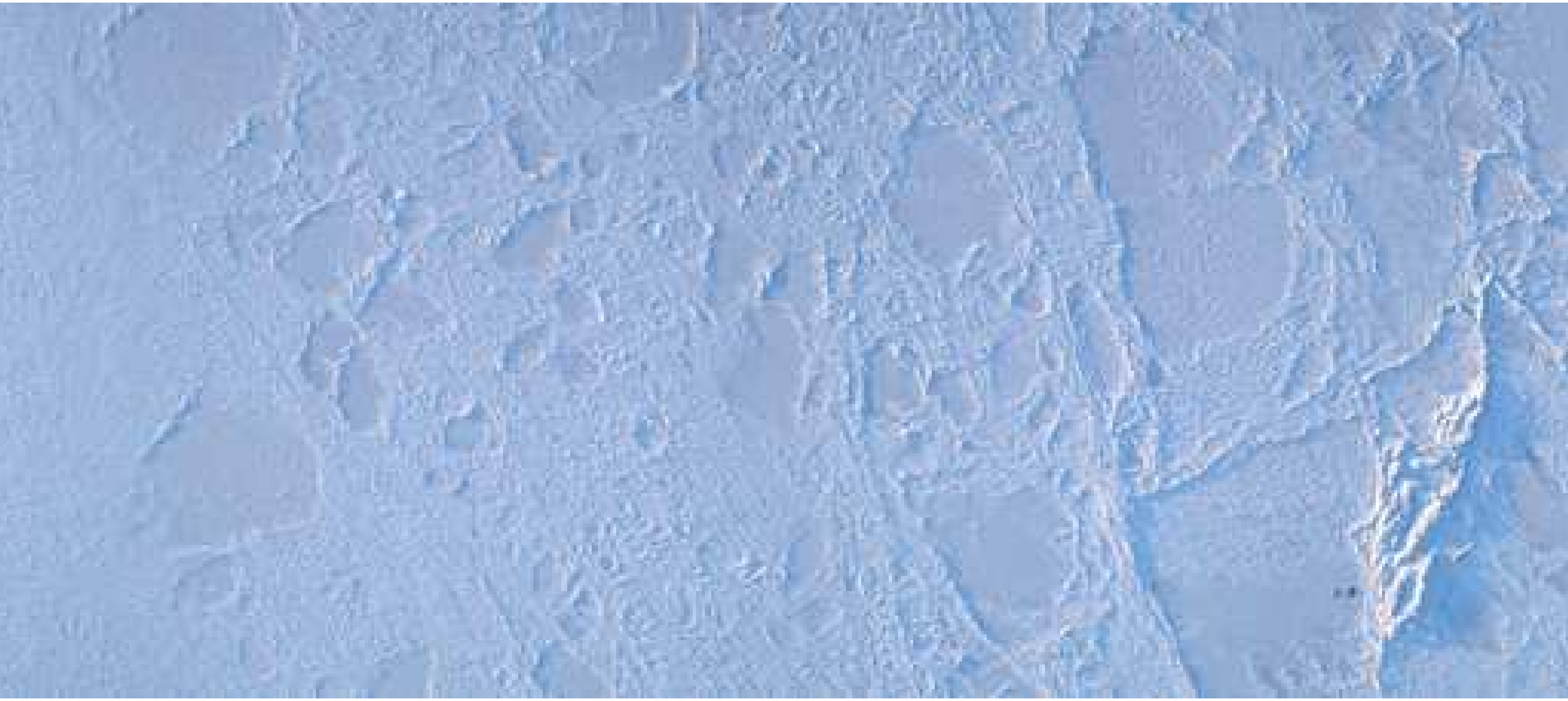
Objectives of Ice Classification

(1) Characterization of sea ice provinces: Establish a unique quantitative description of each sea ice type

(2) Classification: Assign a given object to a surface class, using the characterization

(3) Segmentation: Create a thematic map by applying the classification operator in a moving window

Beaufort Sea



Beaufort Sea, Ridge (March 2003) (J. Maslanik photo)

Rubbled Ice (March 2003) (J. Maslanik photo)

(1.) What is spatial surface roughness?

- a derivative of (micro)topography

$\longrightarrow$ characterization of spatial behavior

(2.) Why do we need surface roughness?

- morphologic characteristics are captured in surface roughness (*not* in absolute elevation)
- subscale information for satellite data

(3.) How do we measure surface roughness? — The GRS !

A UAV with laser profilometer over Barrow

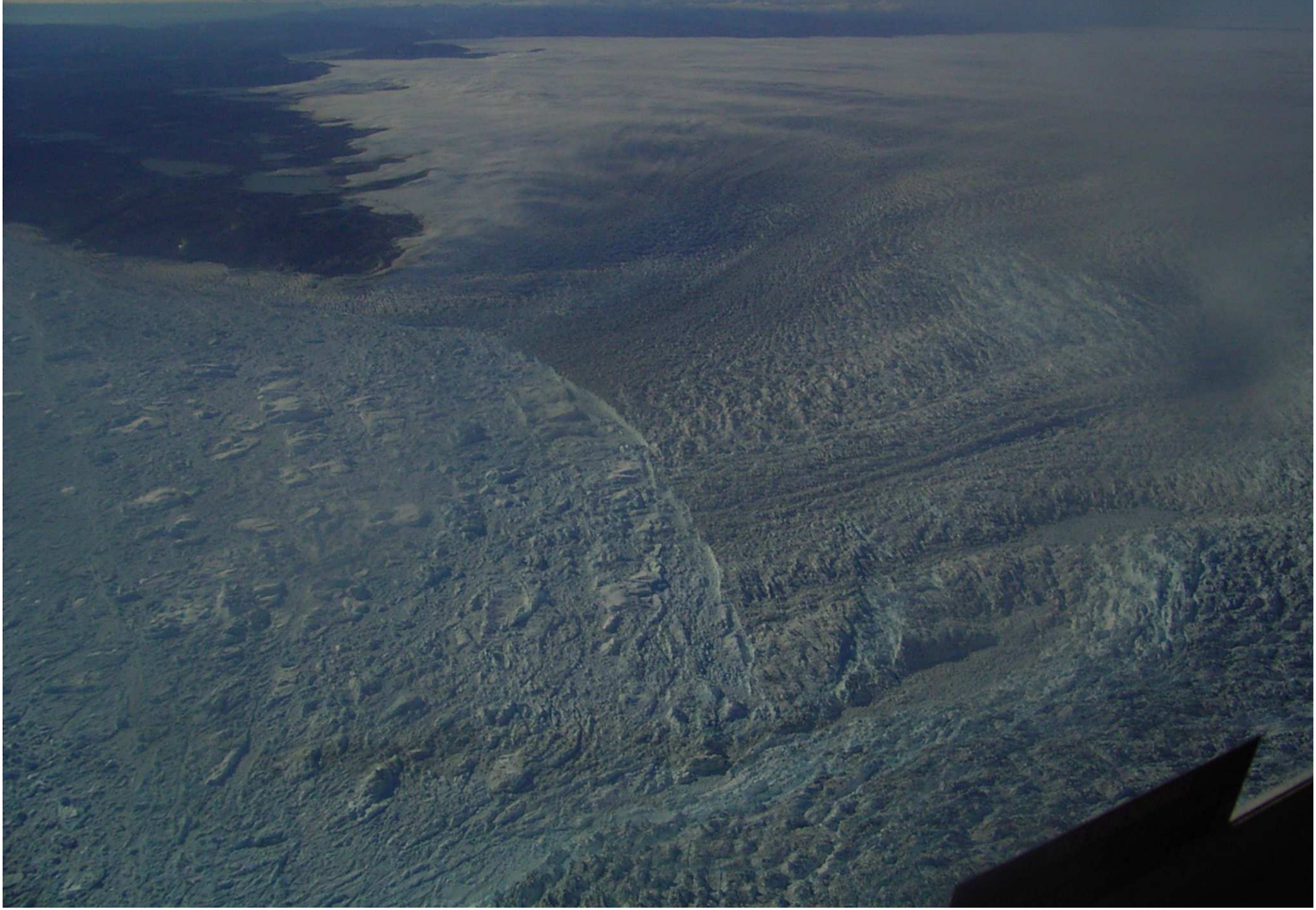
Niwot Ridge Snow Surface: Winter ———————— Summer

Bering Glacier, 1994, mature surge stage, Khittrov Hills in background

Jakobshavn Isbræ Drainage Basin – Spring Ice Surface

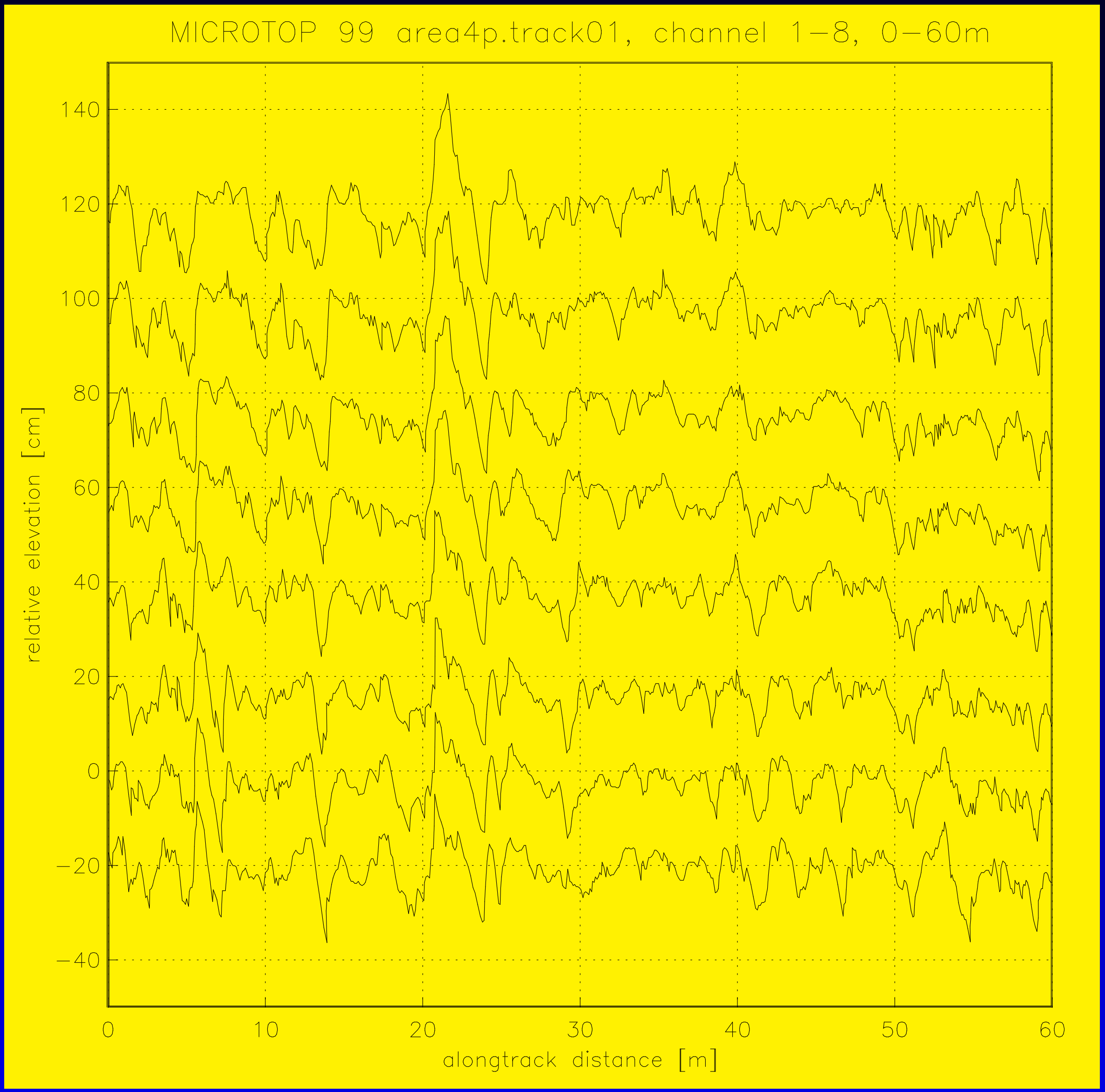
Jakobshavn Isbræ Drainage Basin – Summer Ice Surface

Jakobshavns Isbræ: August 1996



Calving Front of Jakobshavns Isbræ on 16 July 2005

GRS Data – Greenland Ice Sheet



(4.) How do we analyze surface roughness?

The analytically defined spatial derivative needs to be calculated numerically from a data set.
One way to do this:

$$\lim_{x \to x_0} \frac{z(x_0) - z(x)}{x_0 - x}$$

surface slope in a given location x_0

To characterize morphology, better use averages...

Definition of Vario Functions

$V = \{(x,z) \text{ with } x = (x_1, x_2) \epsilon \mathcal{D} \text{ and } z = z(x)\} \subseteq \mathcal{R}^3$

discrete-surface case or

$$V = \{(x,z) \text{ with } x \epsilon \mathcal{D} \text{ and } z = z(x)\} \subseteq \mathcal{R}^2$$

discrete-profile case
Define the *first-order vario function* v_1

$$v_1(h) = \frac{1}{2n} \sum_{i=1}^{n} [z(x_i) - z(x_i + h)]^2$$

with $(x_i, z(x_i)), (x_i + h, z(x_i + h)) \epsilon \mathcal{D}$ and n the number of pairs separated by h.

Higher-Order Vario Functions

The *first-order vario-function set* is

$$V_1 = \{(h, v_1(h))\} = \underline{v}(V_0)$$

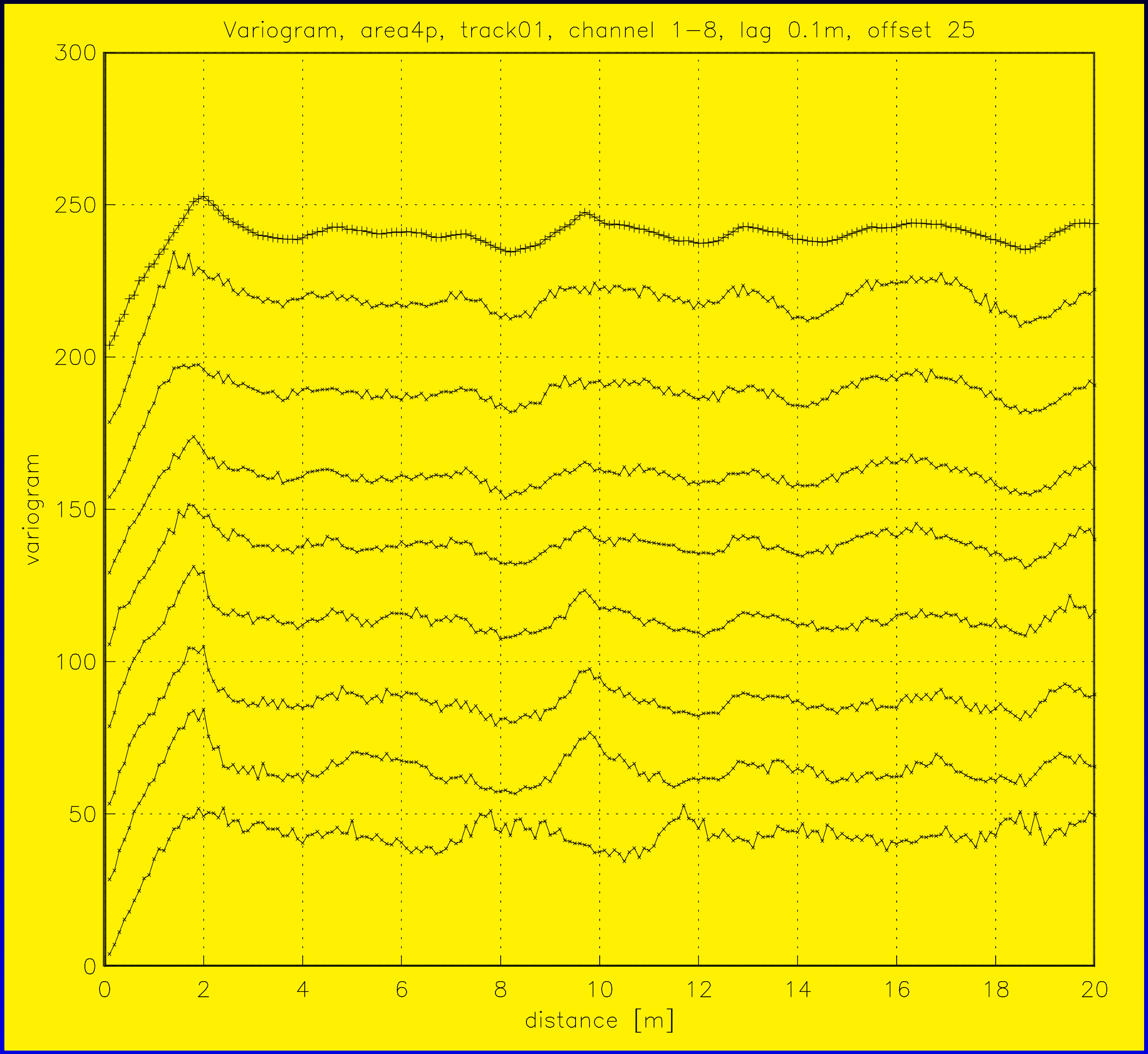
Then: get V_2 from V_1 in the same way you get V_1 from V_0. The second-order vario function is also called *varvar function*.

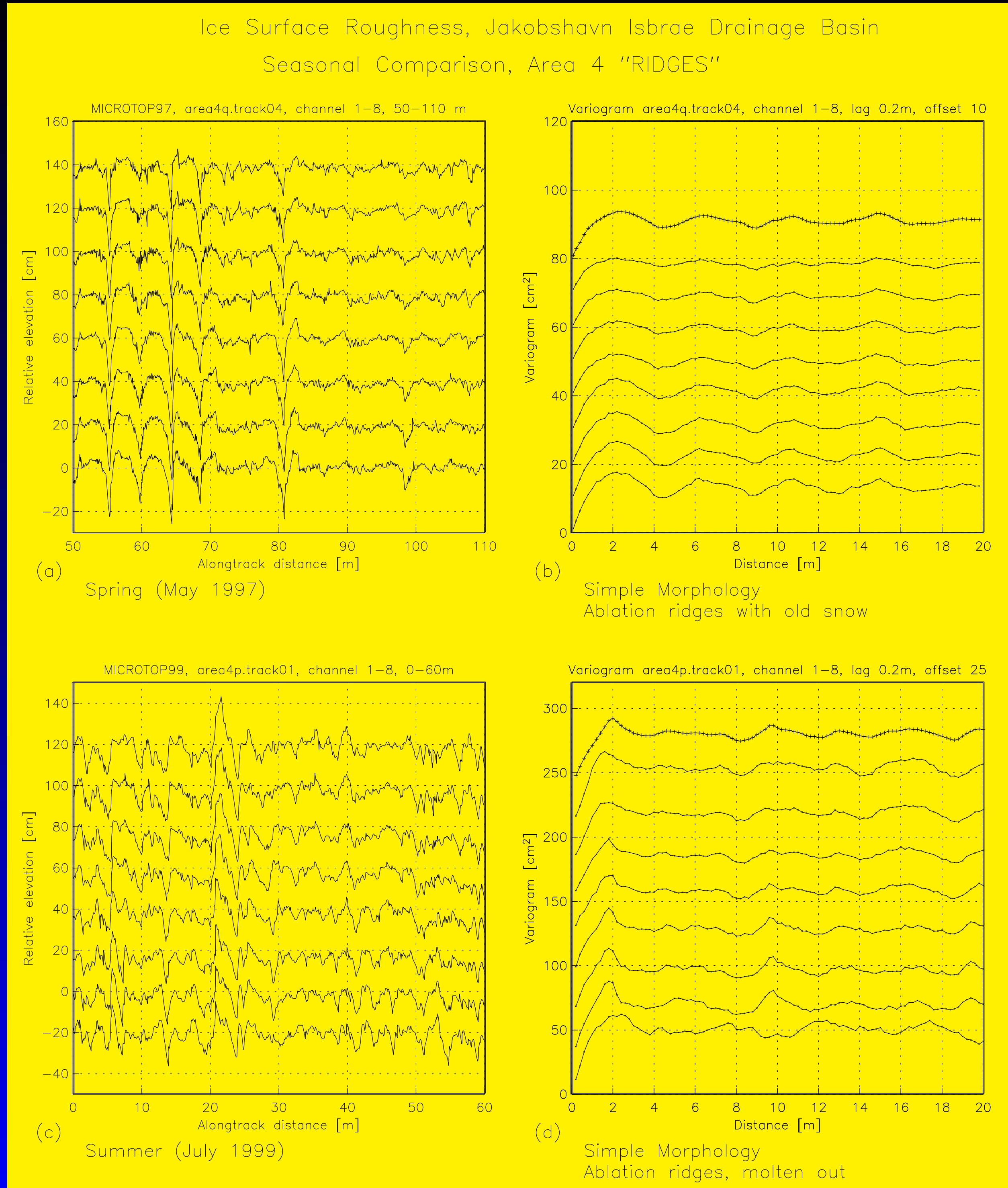
Recursively, the *vario function set of order* $i+1$ is defined by

$$V_{i+1} = \underline{v}(V_i)$$

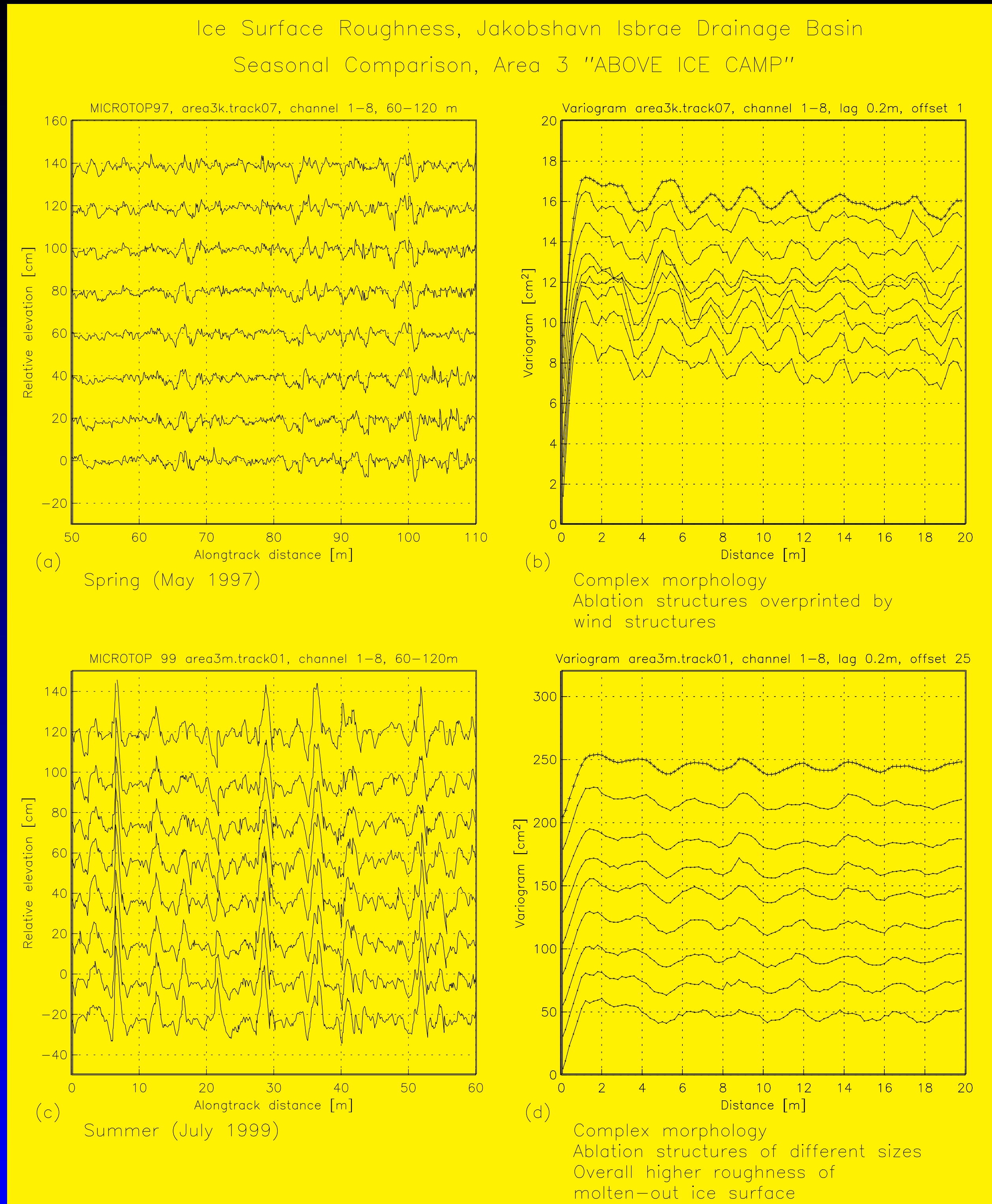
for $i \epsilon \mathcal{N}_0$.

GRS Data – Variogram





Ice Surface Roughness, Jakobshavn Isbrae Drainage Basin
Seasonal Comparison, Area 4 "RIDGES"
MICROTOP97, area4q.track04, channel 1–8, 50–110 m
Relative elevation [cm]
Alongtrack distance [m]
(a)
Spring (May 1997)
Variogram area4q.track04, channel 1–8, lag 0.2m, offset 10
Variogram [cm2]
Distance [m]
(b)
Simple Morphology
Ablation ridges with old snow
MICROTOP99, area4p.track01, channel 1–8, 0–60m
Relative elevation [cm]
Alongtrack distance [m]
(c)
Summer (July 1999)
Variogram area4p.track01, channel 1–8, lag 0.2m, offset 25
Variogram [cm2]
Distance [m]
(d)
Simple Morphology
Ablation ridges, molten out


Ice Surface Roughness, Jakobshavn Isbrae Drainage Basin
Seasonal Comparison, Area 3 "ABOVE ICE CAMP"
MICROTOP97, area3k.track07, channel 1–8, 60–120 m
Relative elevation [cm]
Alongtrack distance [m]
(a)
Spring (May 1997)
Variogram area3k.track07, channel 1–8, lag 0.2m, offset 1
Variogram [cm²]
Distance [m]
(b)
Complex morphology
Ablation structures overprinted by
wind structures
MICROTOP 99 area3m.track01, channel 1–8, 60–120m
Relative elevation [cm]
Alongtrack distance [m]
(c)
Summer (July 1999)
Variogram area3m.track01, channel 1–8, lag 0.2m, offset 25
Variogram [cm²]
Distance [m]
(d)
Complex morphology
Ablation structures of different sizes
Overall higher roughness of
molten–out ice surface

Geostatistical Classification

Steps:

(1) Select a window in the study area

(2) Calculate vario function(s) for data in the window

(3) Filter the function in (2) [optional]

(4) Calculate vario parameters (geostatistical classification parameters) from (2) or (3)

(5) Compose a feature vector of parameters

(6) Associate the surface in the window (1) to a class by

  (a) deterministic algorithm

  (b) connectionist association (neural net)

  (c) multivariate statistical classification

Geostatistical Classification Parameters

significance parameters:
slope parameter:

$$p1 = \frac{\gamma_{max_1} - \gamma_{min_1}}{h_{min_1} - h_{max_1}}$$

relative significance parameter:

$$p2 = \frac{\gamma_{max_1} - \gamma_{min_1}}{\gamma_{max_1}}$$

pond – maximum vario value
mindist – distance to first min after first max

$$avgspac = \frac{1}{n} \sum_{i=1}^{n} \frac{1}{i} h_{min_i}$$

Parameters for complex morphology

Define $p2$-type parameters $pt2(\cdot,\cdot)$ as

$$pt2(max_i, min_j) = \frac{\gamma_{max_i} - \gamma_{min_j}}{\gamma_{max_i}}$$

for $i \leq j$.
With this notation, we define significance parameters for the first few minima in the vario function:

$$p3 = pt2(max_1, min_2)$$

$$p4 = pt2(max_2, min_2)$$

$$p5 = pt2(max_s, min_2)$$

Feature vectors

Parameters are composed into *feature vectors*, on which the classification is based.

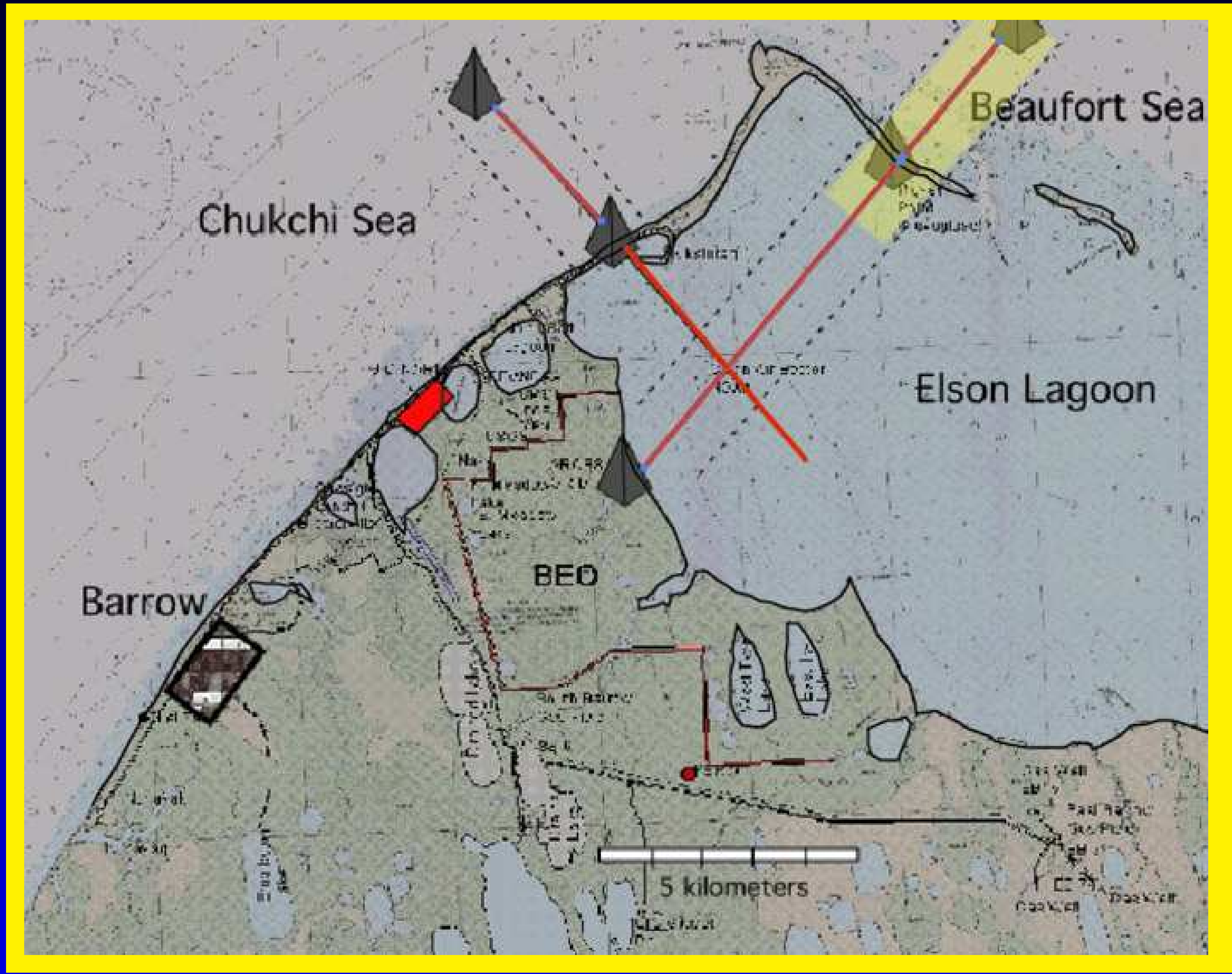
Selection of parameters depends on the applied problem.

Characteristic Snow Forms

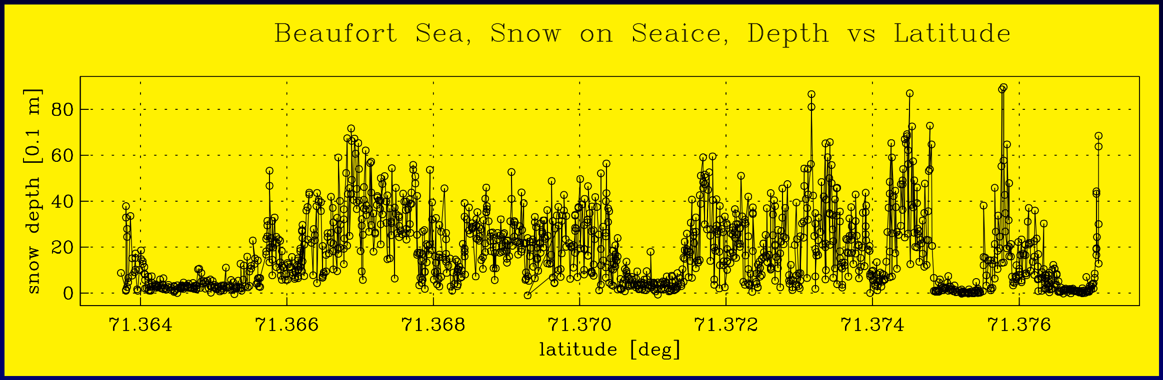
Winter sastrugi	**Summer** sun cups
rougher	smoother
pond high	*pond* low
complexely shaped surface	regularly, evenly shaped surface
large size range of features	well-defined characteristic sizes
$min_a = 2$ m	$min_a = 0.4$-0.6 m $min_b = 2.2$-2.4 m $min_c = 7$ m
avgspac often not defined	*avgspac* well defined
deriv high	*deriv* low
narrow first *max* significant first *min*	$min - max$ sequence with regular multiples

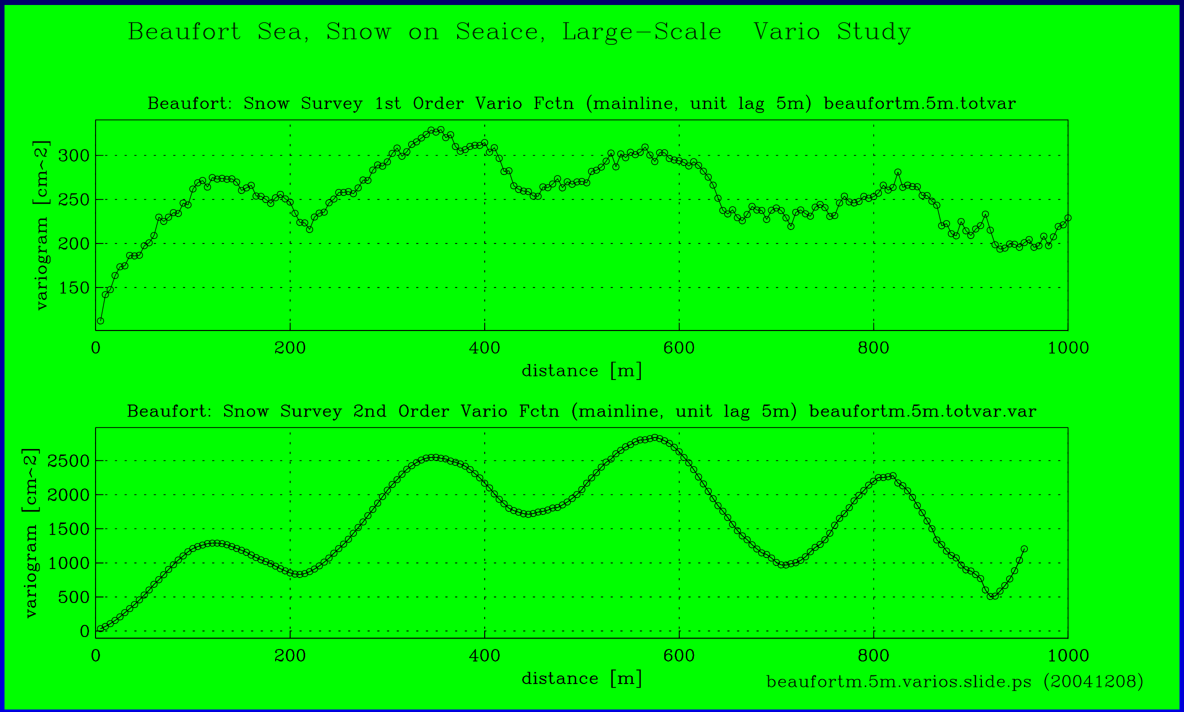
Sea Ice in the Alaskan Arctic

Characterization and Segmentation
of Sea-Ice Provinces
Using Hyperparameters
in Geostatistical Classification

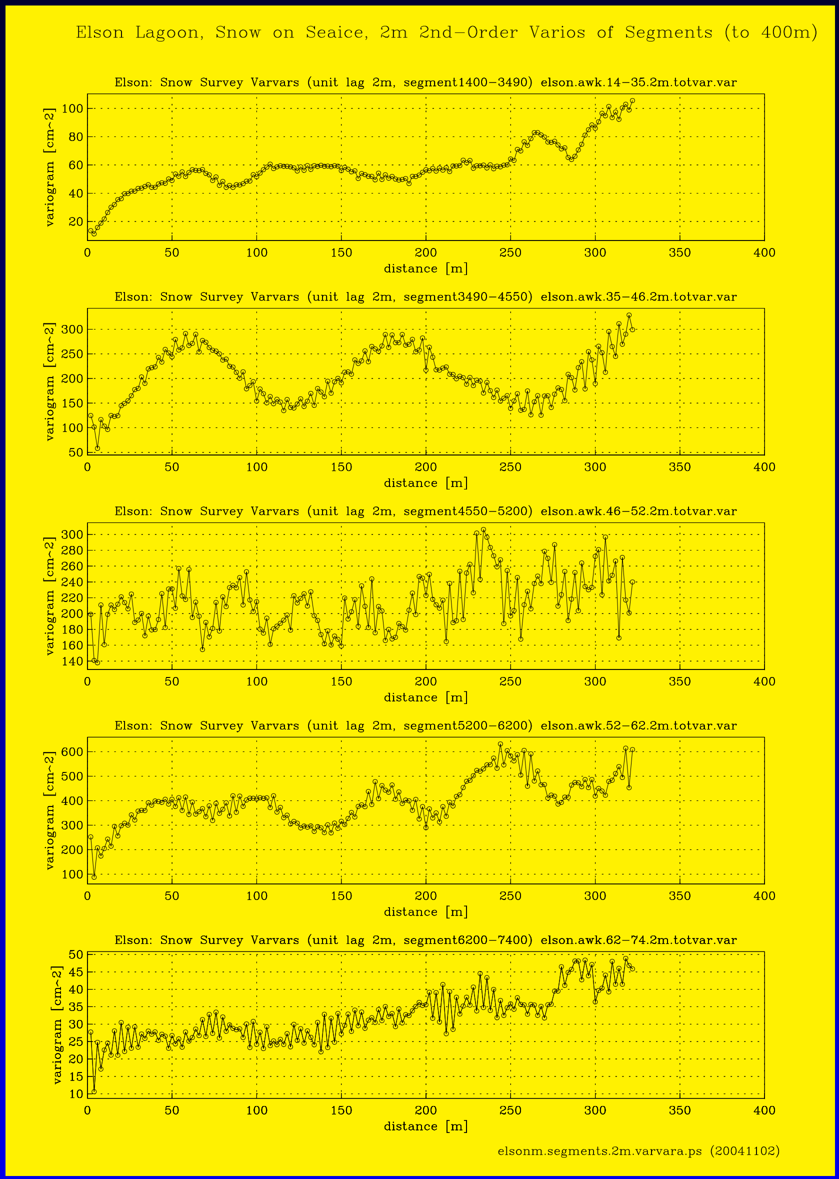

Beaufort Sea
Chukchi Sea
Elson Lagoon
BEO
Barrow
5 kilometers

Beaufort Sea





Elson Lagoon Profile: varvar functions



Robust search for hyperparams in complex geo-data sets

Determine *bigmax*, the largest maximum in a group of g maxima:

$$\gamma_{bigmax} = \max\{\gamma_{max_1}, \ldots, \gamma_{max_g}\}$$

say, $\gamma_{bigmax} = gamma_{max_k}$, some $k \epsilon \{1, \ldots, g\}$

$$h_{bigmax} = h_{max_k}$$

Then determine *bigmin*, the smallest minimum in a group of g minima following *bigmax*:

$$\gamma_{bigmin} = \min\{\gamma_{min_k}, \ldots, \gamma_{min_{k+g-1}}\}$$

say, $\gamma_{bigmin} = gamma_{min_r}$, some $r \epsilon \{k, \ldots, k+g-1\}$

$$h_{bigmin} = h_{max_r}$$

Important hyperparameters

Then:

$$pt1(bigmax, bigmin) = pt1(max_k, min_r)$$
$$pt2(bigmax, bigmin) = pt2(max_k, min_r)$$

Generalization: Determine all $bigmax_i$ and $bigmin_j$ analogously for a given groupsize g.

$$pt*(bigmax_i, bigmin_j) \quad \text{for} \quad * = 1, 2$$

Generalization: Determine the best groupsize automatically

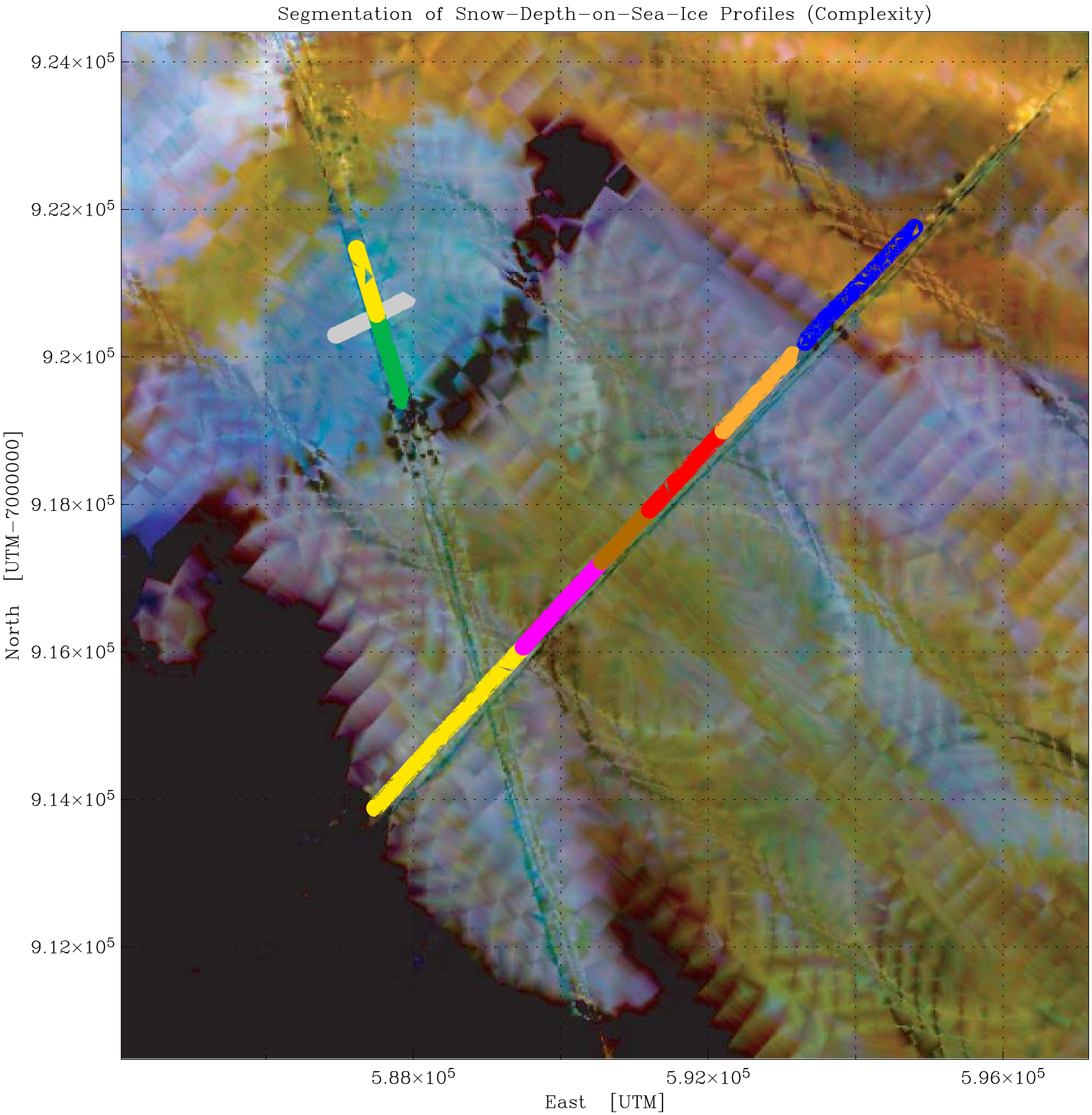
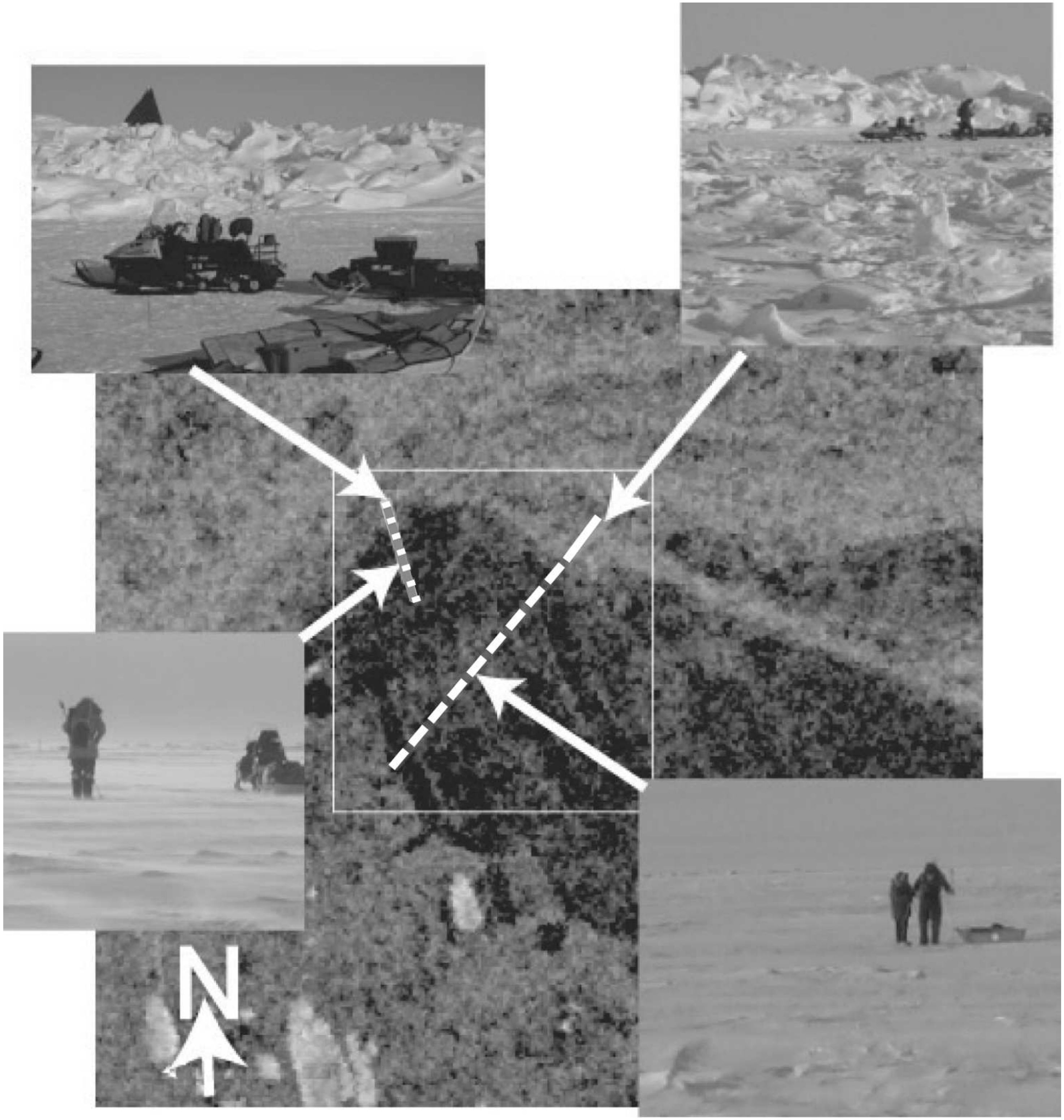

Segmentation of Snow-Depth-on-Sea-Ice Profiles (Complexity)
North [UTM-7000000]
9.24×10^5
9.22×10^5
9.2×10^5
9.18×10^5
9.16×10^5
9.14×10^5
9.12×10^5
5.88×10^5
5.92×10^5
5.96×10^5
East [UTM]

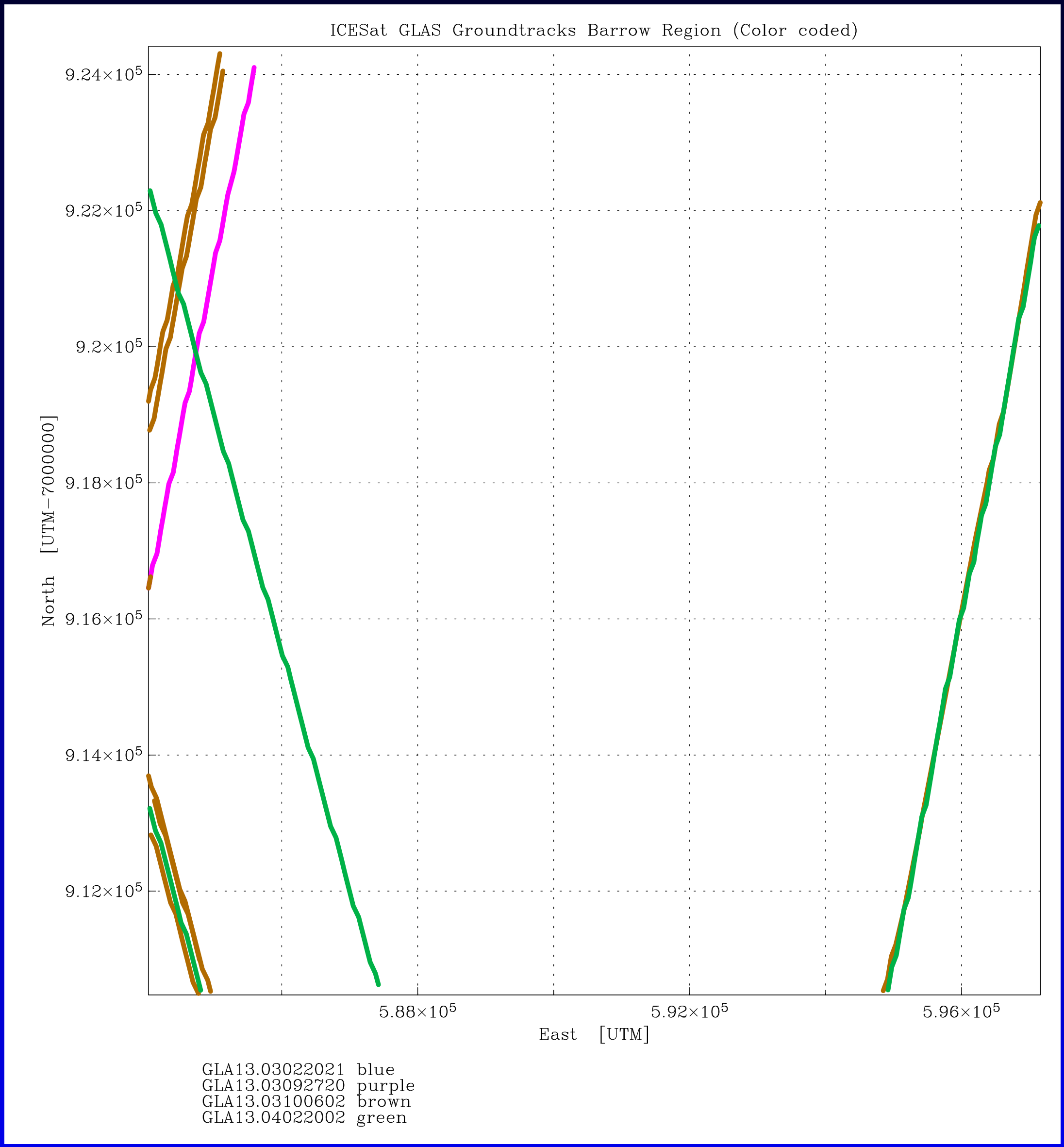
Table 1. Arctic Sea-Ice Classes near Point Barrow — Geostatistical Characterization

	z_0	$z_0(SLT)$	$pond$	$mindist_{big}$	$p1big$	$p2big$	**description**	**development stage**	**complexity**	**sea-ice class**
Beaufort Type	6.42	12.83	329	210	5.4	0.35	organization at large scale (210m); highly rubbled / ridged at smaller scale; large small-scale features of intermediate–high significance	late	f+	deformed ice
beaufort.sub1 (75-81)	6.43	12.86	331	25	5.0	0.092	ridges (subunit of Beaufort Type)	late	[subunit]	deformed ice
beaufort.sub2 (82-85)	10.36	20.72	850	50	117.4	0.5	very highly ridged (subunit of Beaufort Type)	late	[subunit]	deformed ice
Elson Type	3.18	6.36	81	—	—	—	small-scale features more significant than large ones, heterogeneous, low roughness	several	several	several
Elson segment 1 (14-35)	3.09	6.18	76.39	86	0.7	0.22	surface disturbed after freezing, no organized large features	early transitional	a	embayment ice
Elson segment 2 (35-46)	3.50	7.0	98.04	116	2.7	0.54	large-scale features dominant, organized at large scale	late	e	grounded ice, dynamically undisturbed
Elson segment 3 (46-52)	3.72	7.43	110.47	68	7.32	0.40	high roughness, highly complex, not much organization	intermediate transitional	c	transitional ice
Elson segment 4 (52-62)	4.46	8.92	159.29	144	2.62	0.36	very high roughness, increasing large-scale organization	later transitional	d	later-stage-transitional ice
Elson segment 5 (62-72)	2.62	5.24	55	138	0.18	0.34	2m and 20m features dominate large-scale (138m) features, relatively large disturbances	early intermediate transitional	b	shore-fast ice (no seaward dynamics)

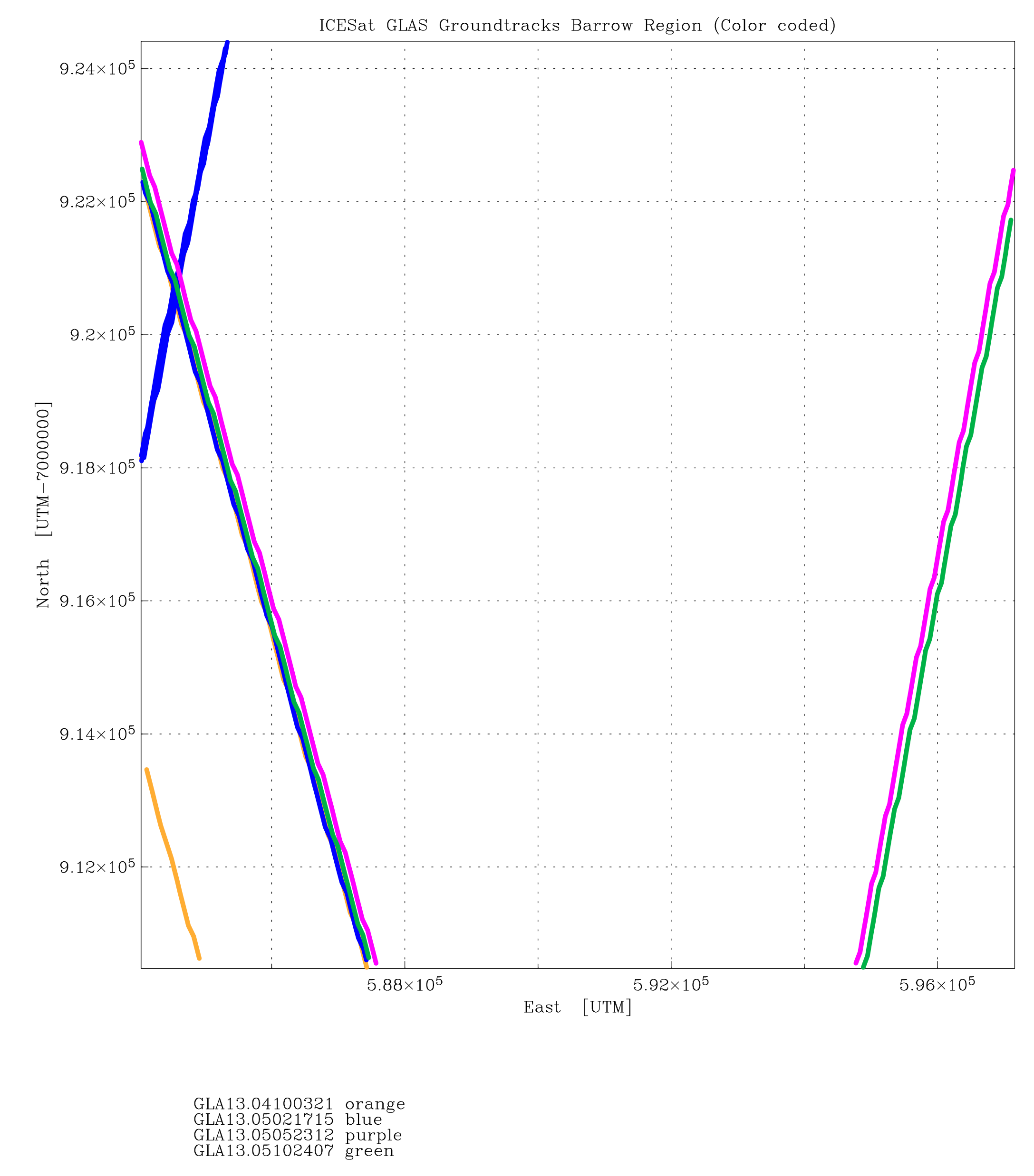

N

Roughness and Spatial Variability in GLAS Data

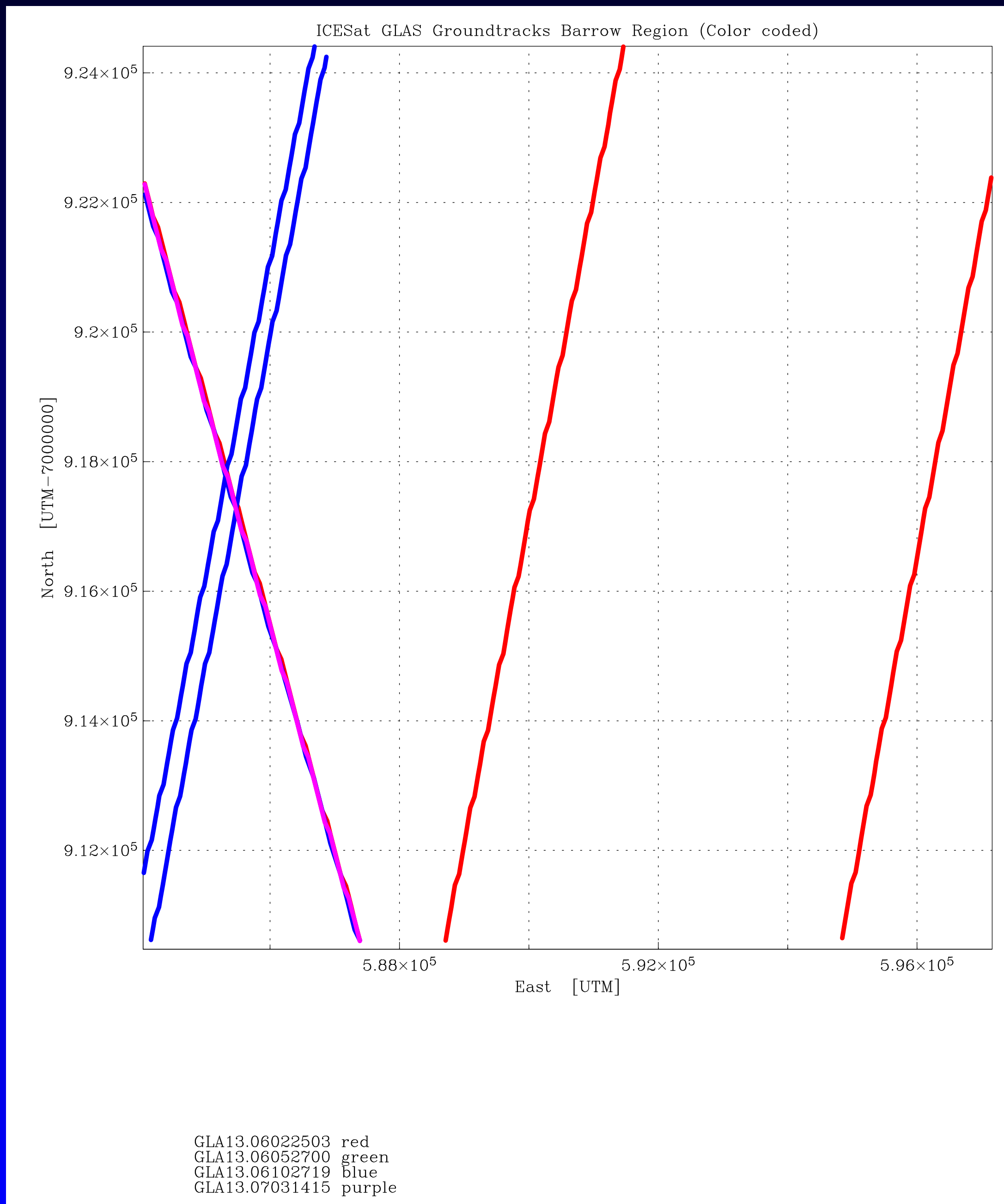
GLAS Tracks: Barrow Area [1]



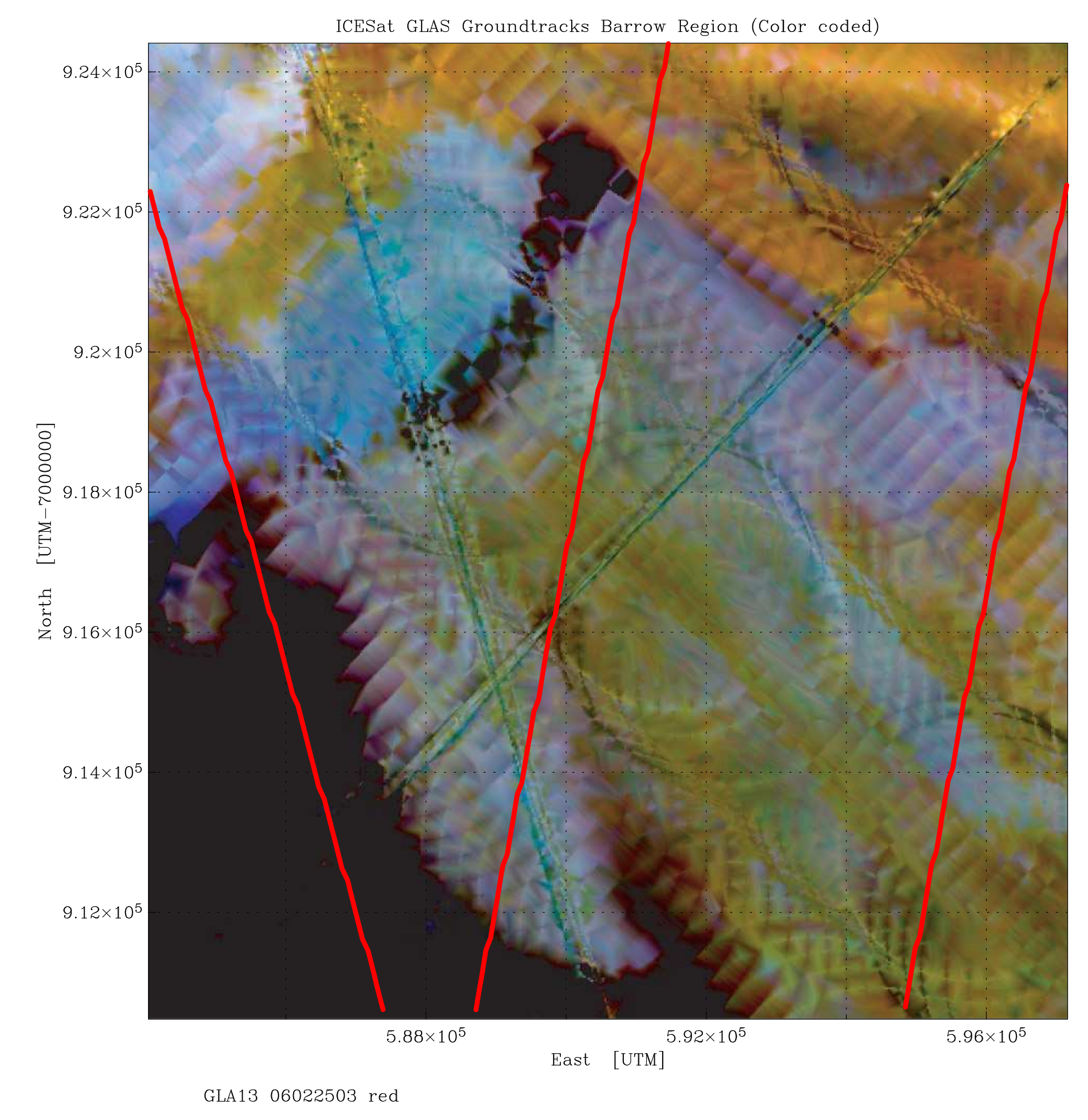
GLAS Tracks: Barrow Area [2]



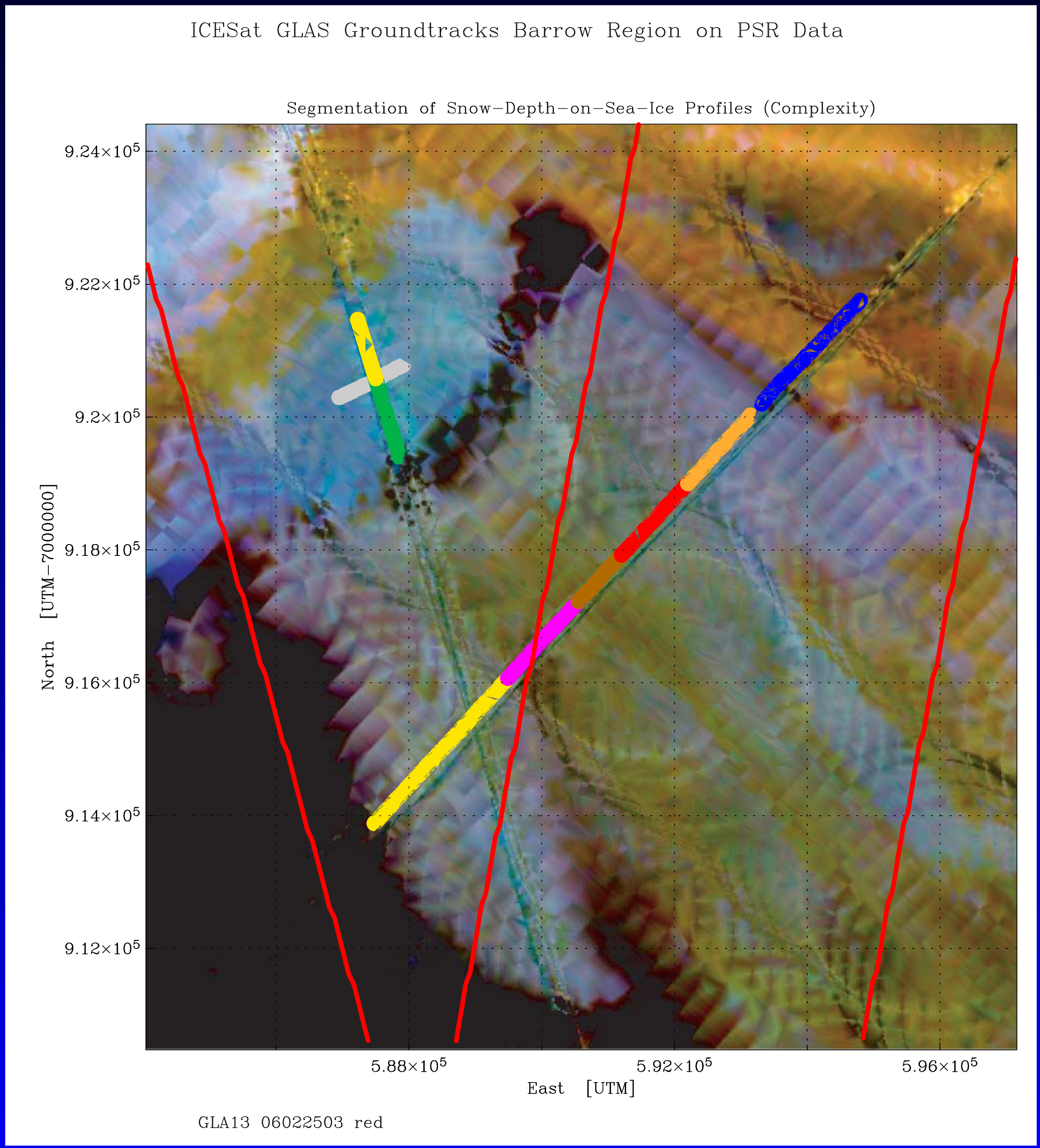
GLAS Tracks: Barrow Area [3]



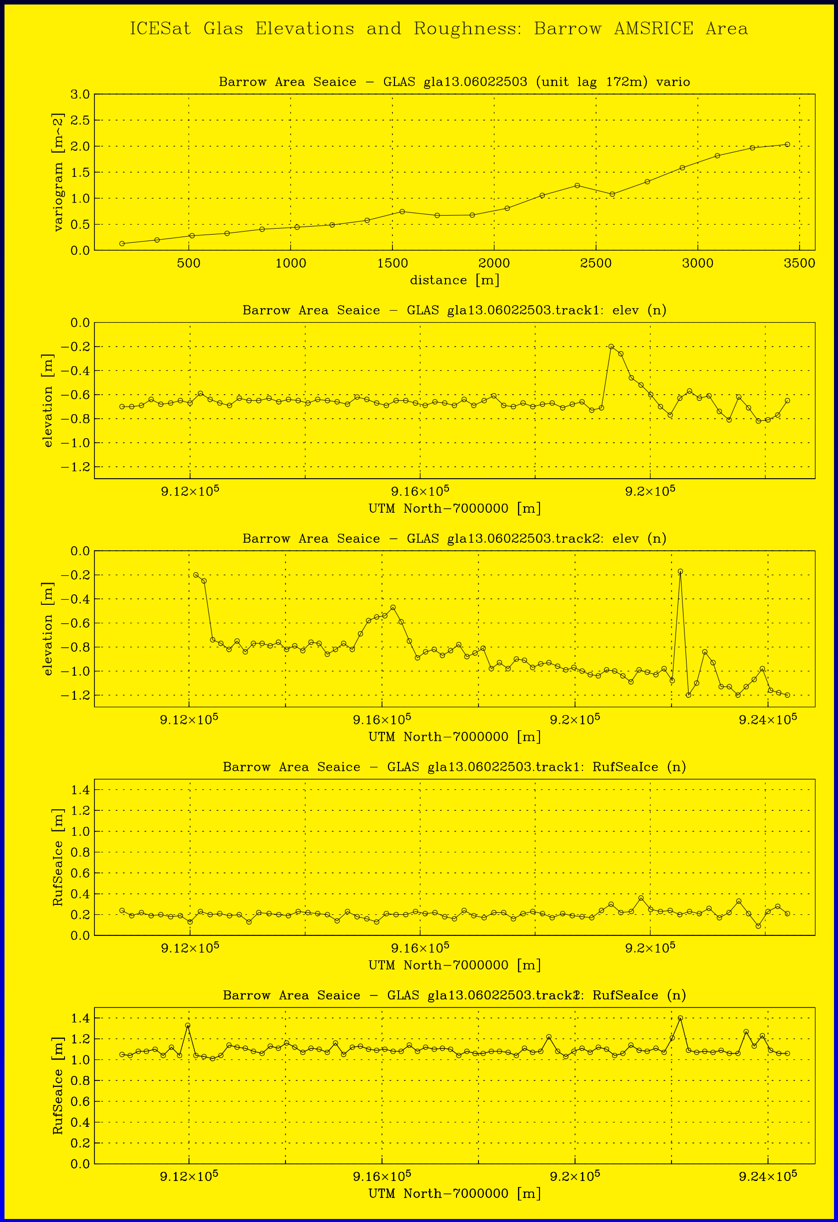
GLAS Tracks: Barrow Area [3.1] Feb/March 2006 L3E



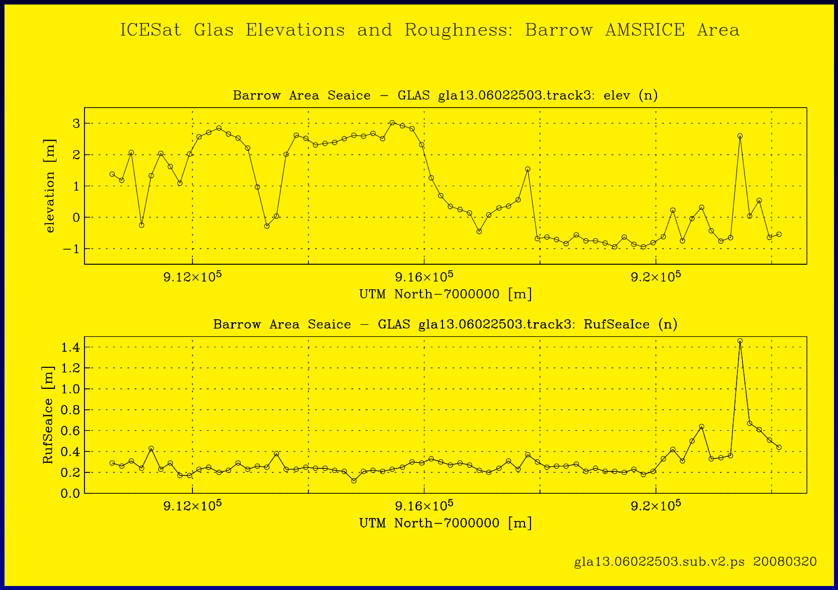
GLAS Tracks L3E with PSR and Snow-Depth Segmentation



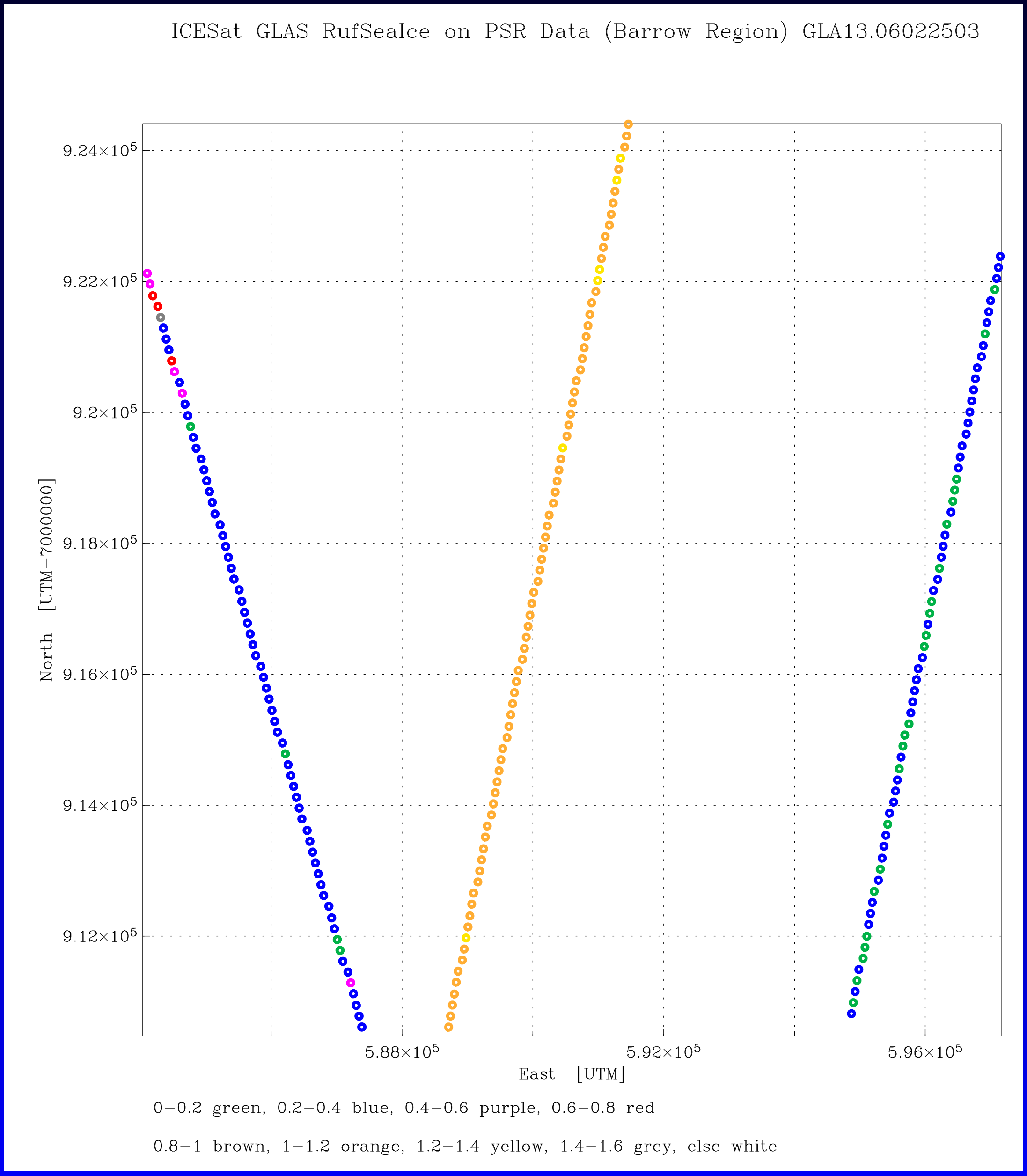
GLA13 Feb/March 2006 Barrow (L3E, rel28): Vario, Elev, RufSeaIce



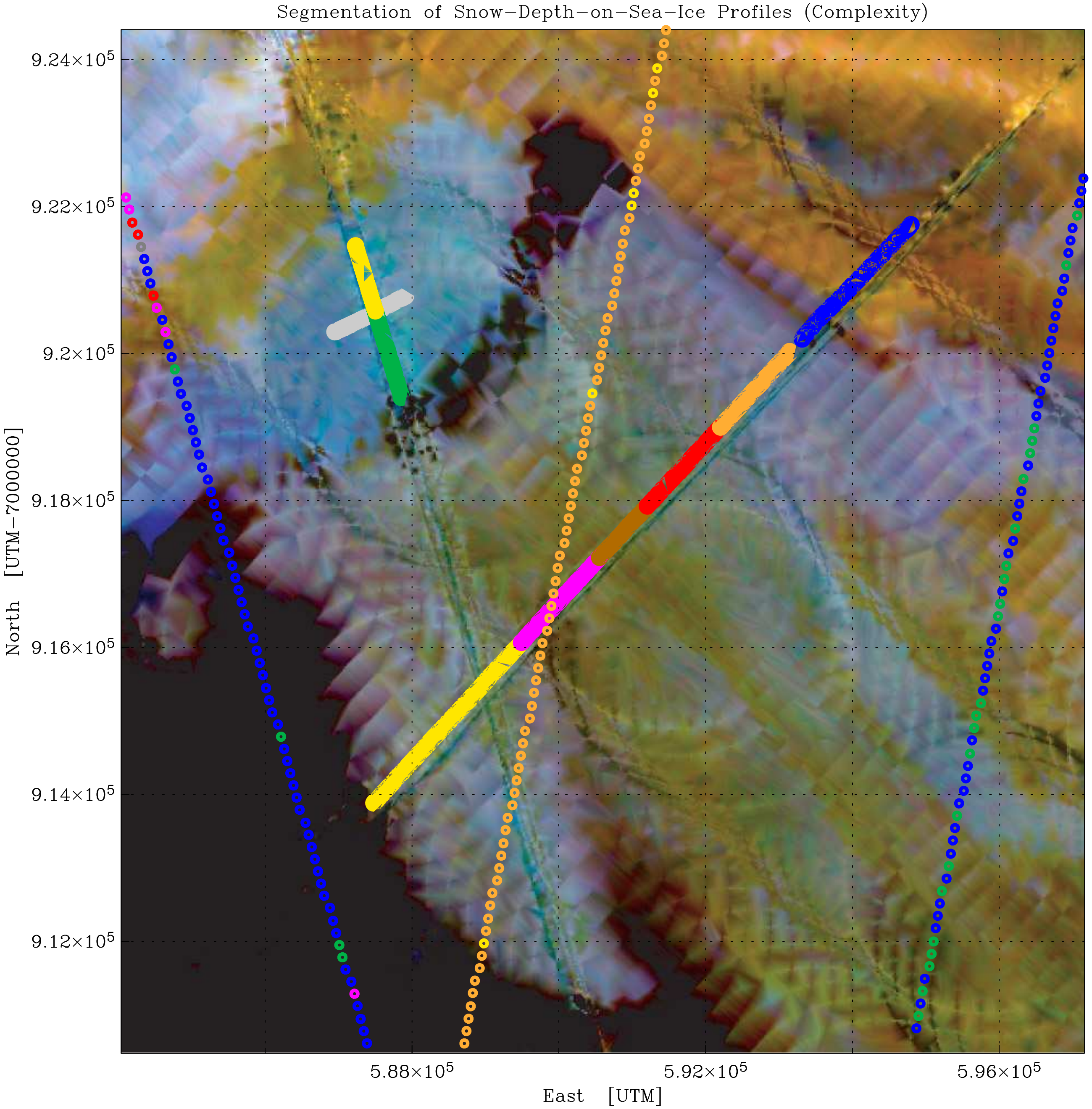
GLA13 Feb/March 2006 Barrow (L3E, rel28): Elev, RufSeaIce



GLAS Tracks L3E: Color By Ruf



ICESat GLAS RufSeaIce on PSR Data (Barrow Region) GLA13.06022503

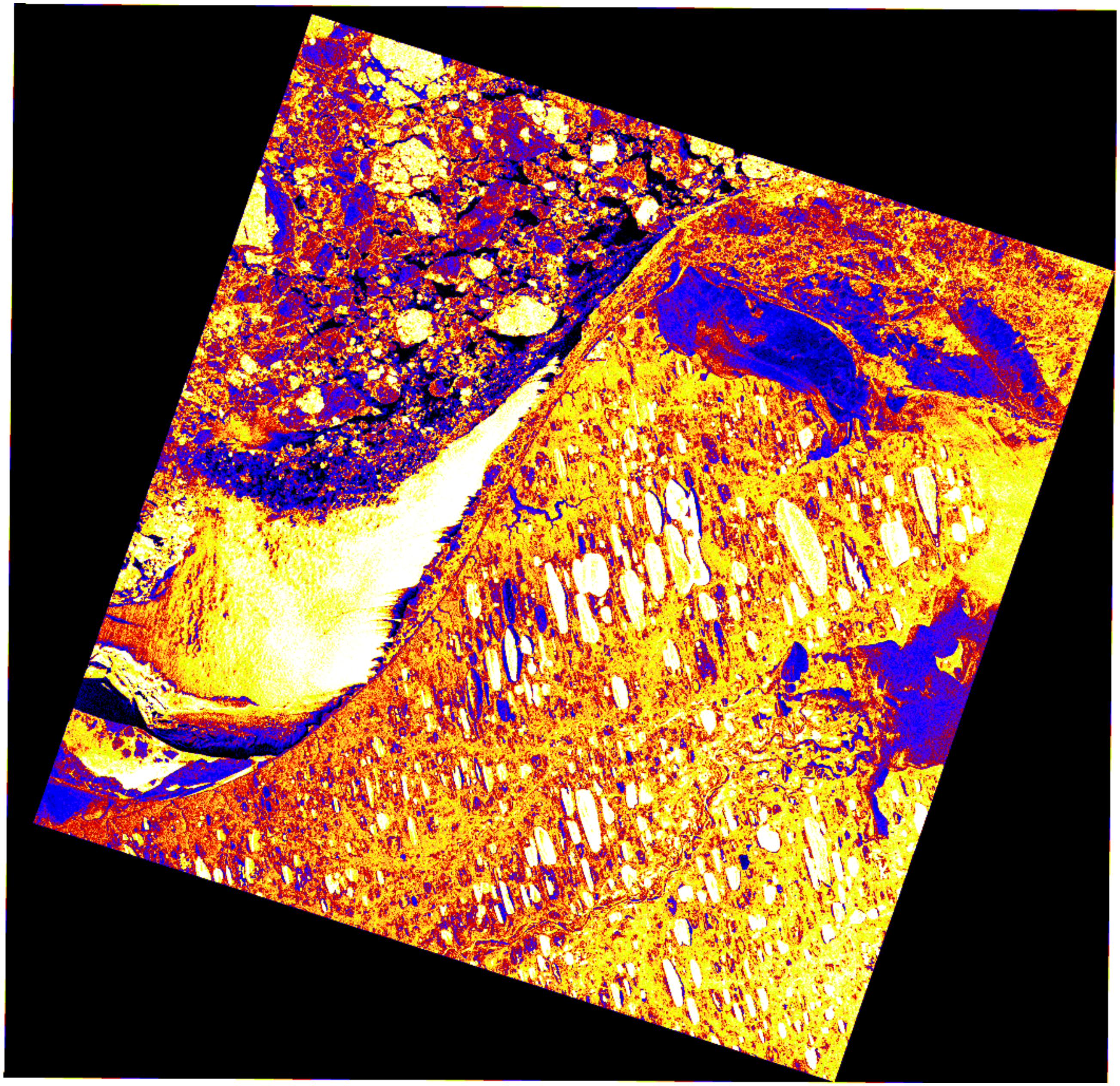


0-0.2 green, 0.2-0.4 blue, 0.4-0.6 purple, 0.6-0.8 red

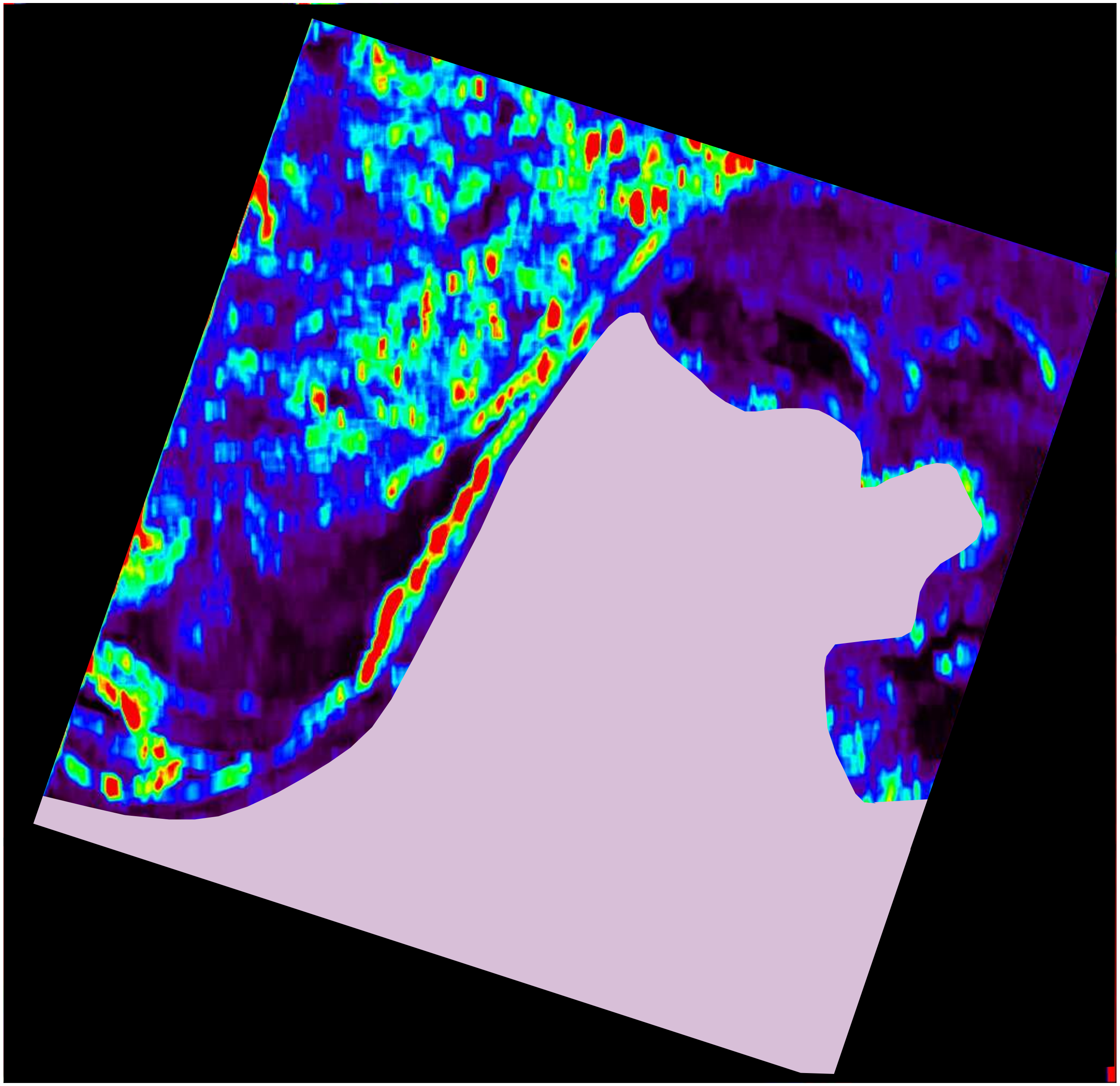
0.8-1 brown, 1-1.2 orange, 1.2-1.4 yellow, 1.4-1.6 grey, else white

Classification of RADARSAT SAR data

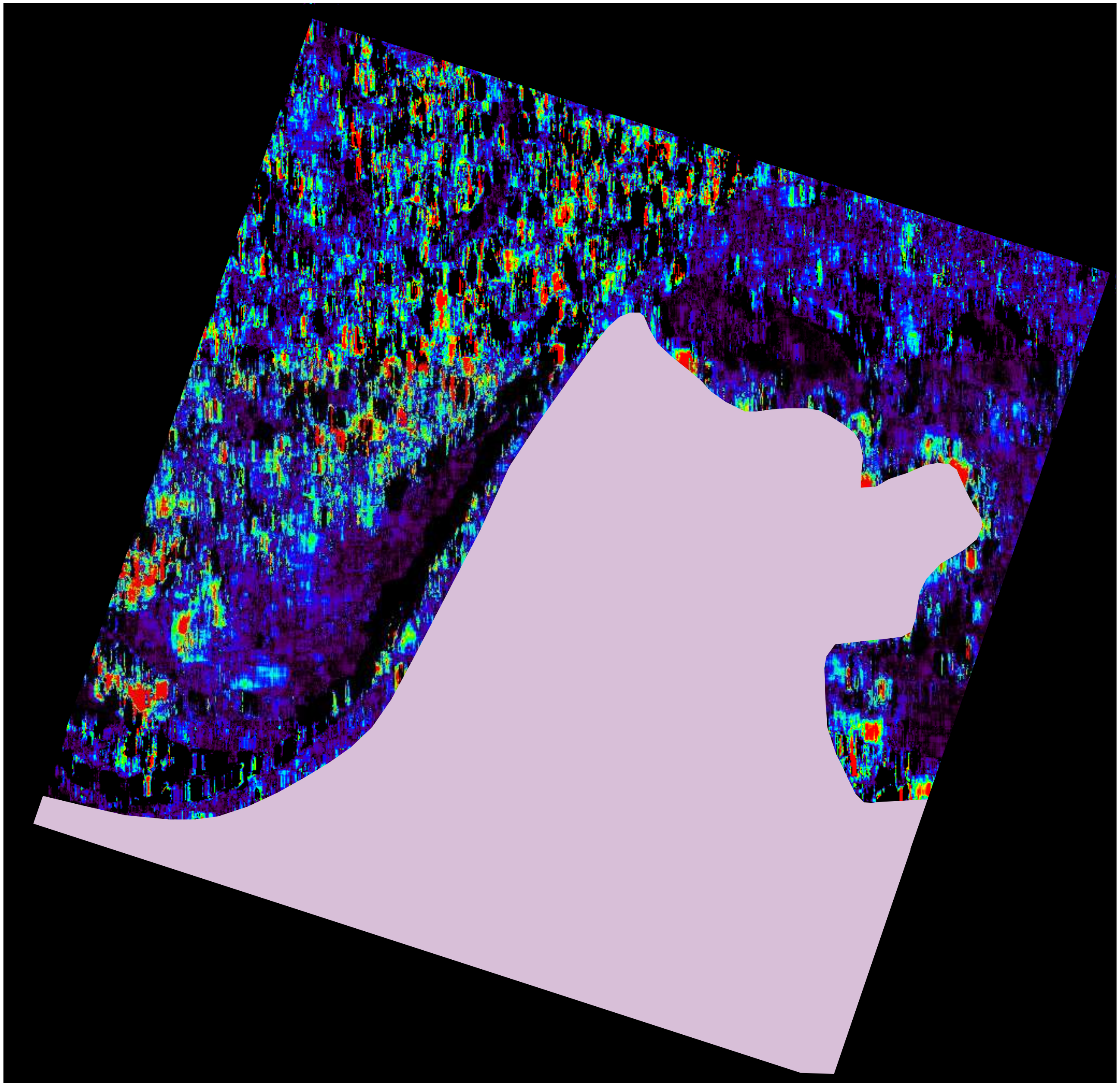
RADARSAT Data (March 2003)



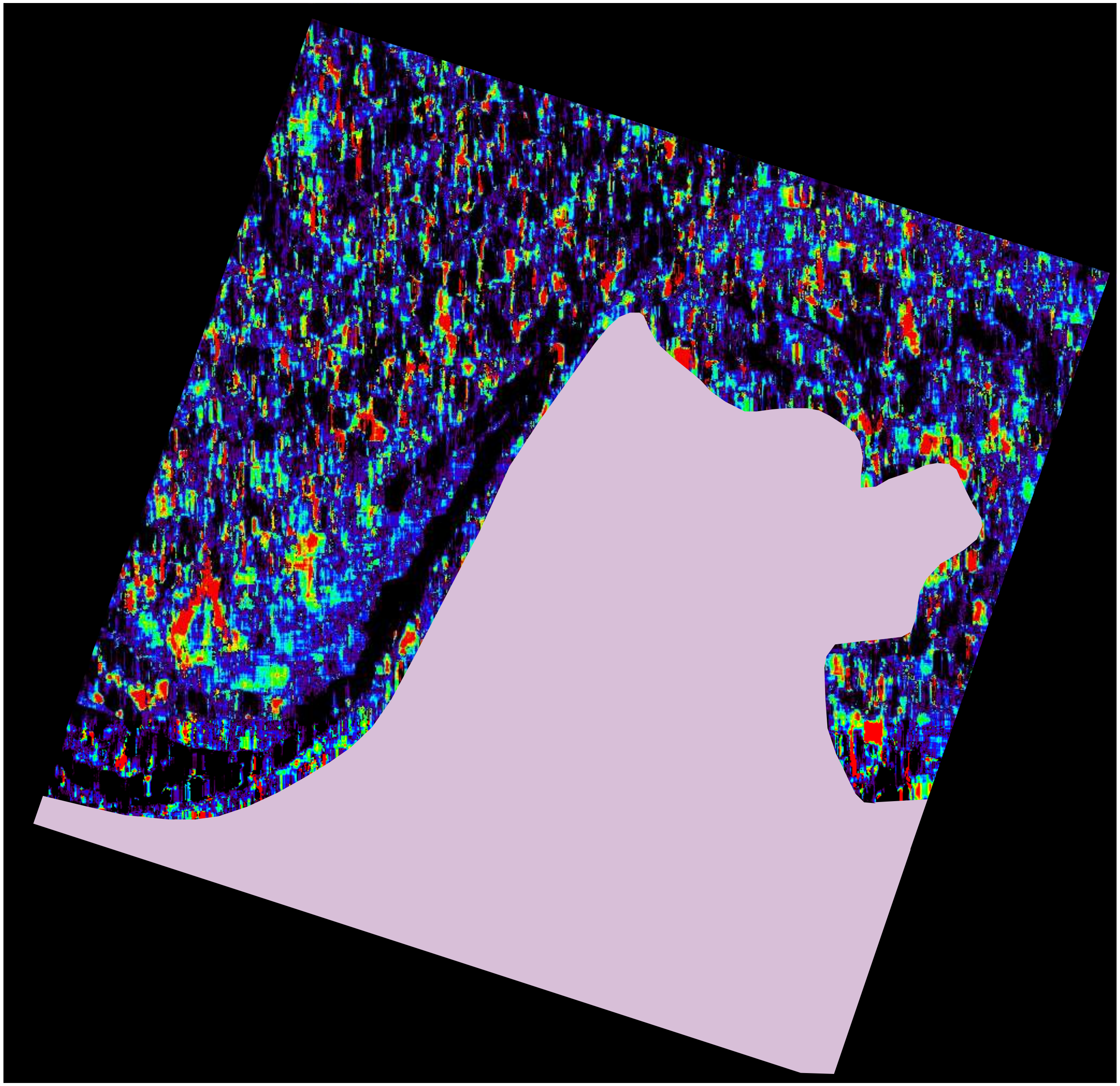
Parameter Map: pond



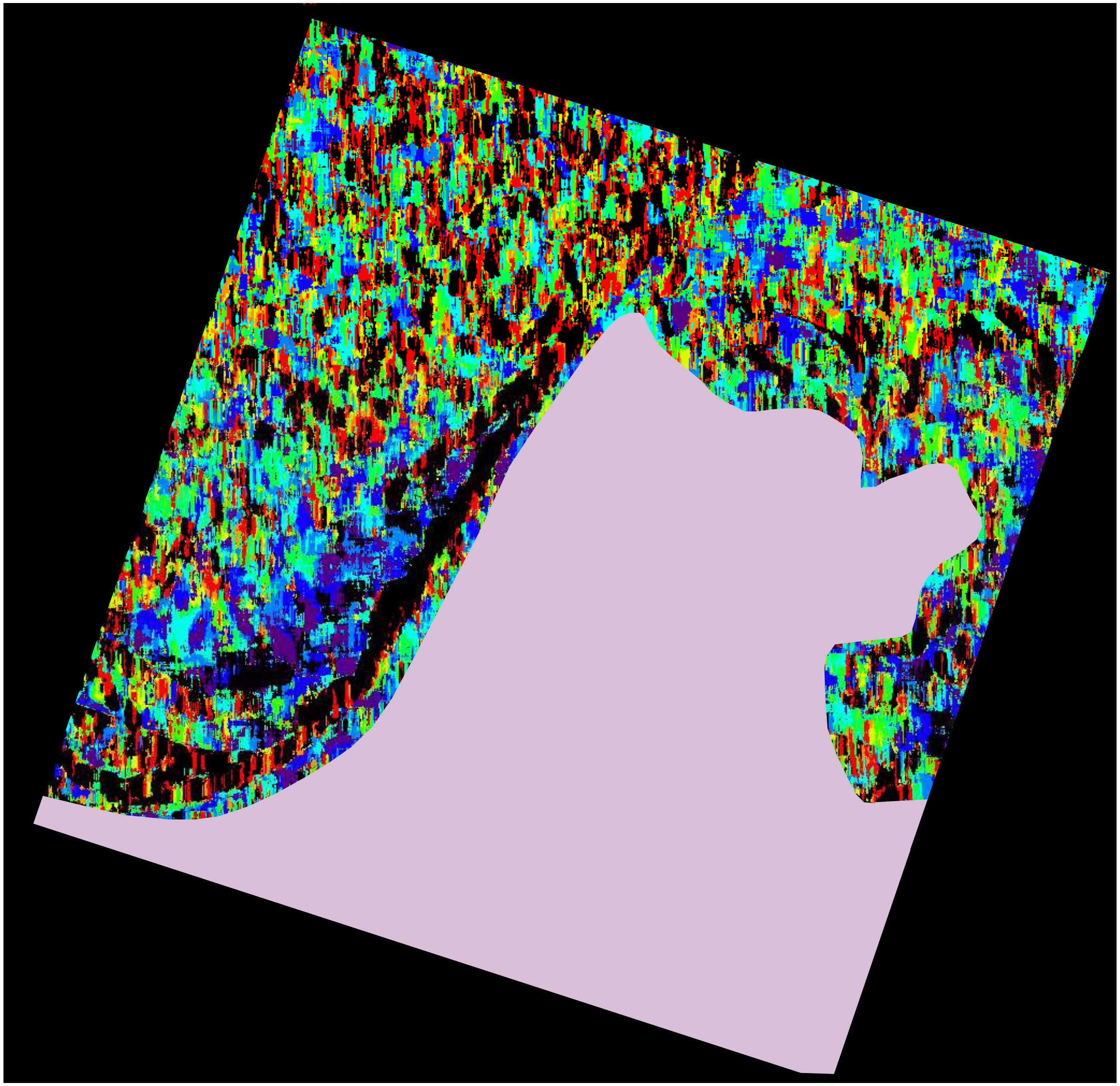
Parameter Map: p1



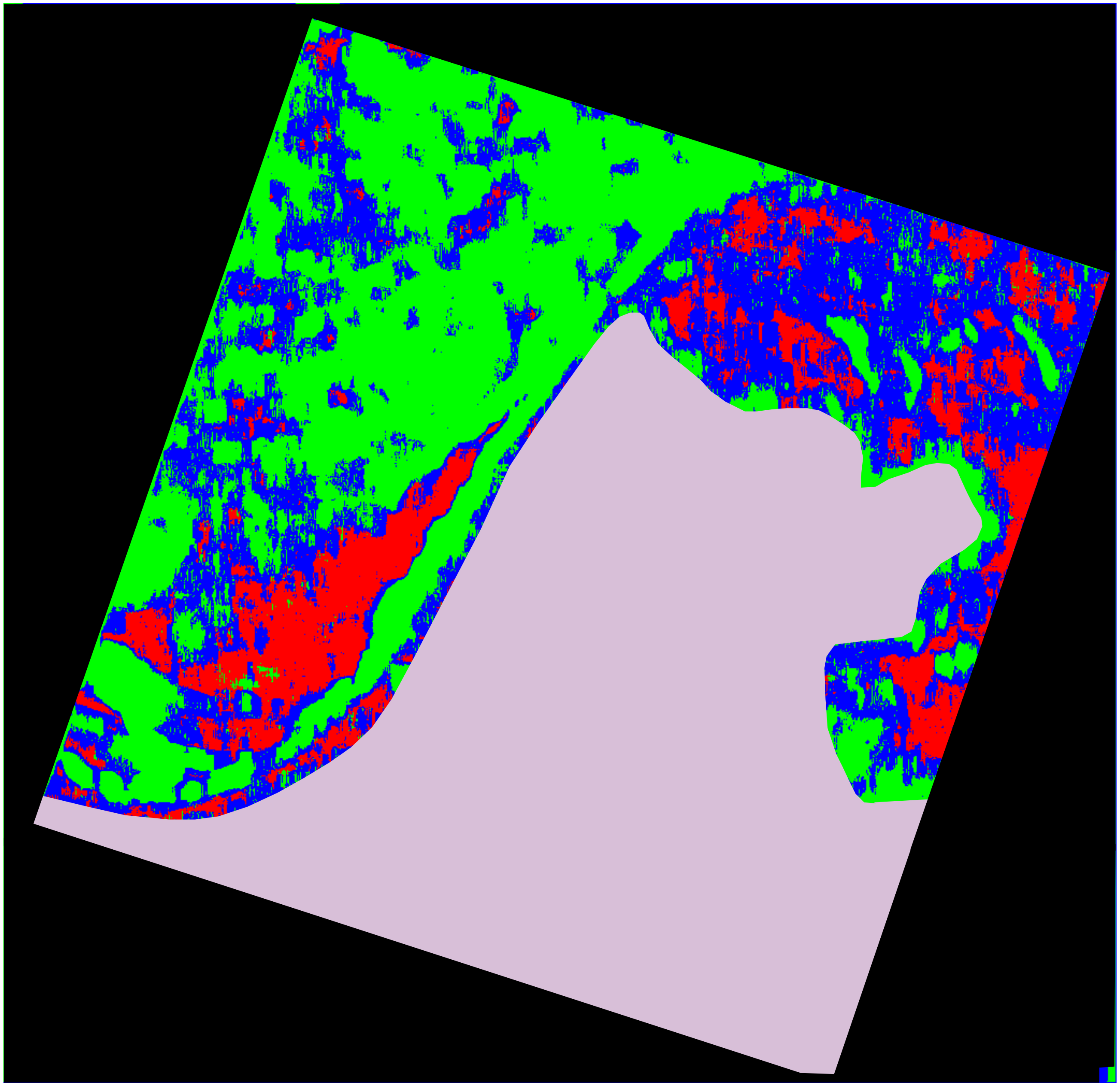
Parameter Map: p2



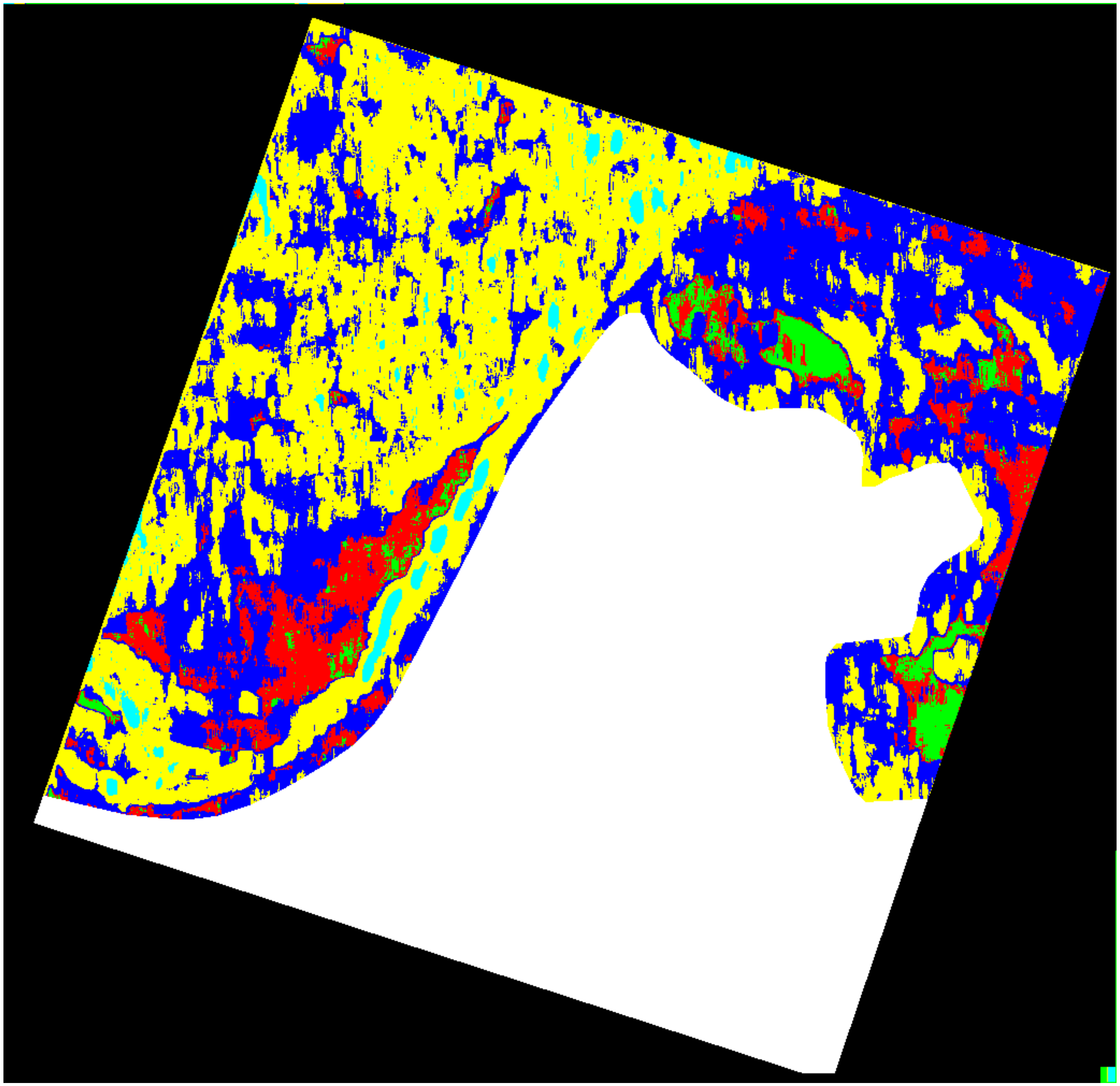
Parameter Map: mindist



Maximum Likelihood Classification Based on 4 Parameter Maps (3 Classes)



Maximum Likelihood Classification Based on 4 Parameter Maps (5 Classes)



Applications

- Subscale information for ground truthing of (new) satellite sensors
- Deformation and dynamics of icestreams
- Characterization of seaice types
- Derivation of aerodynamic roughness length from data
- Importance of surface roughness for ablation

Changes in Amundsen Sea Glaciers, Antarctica

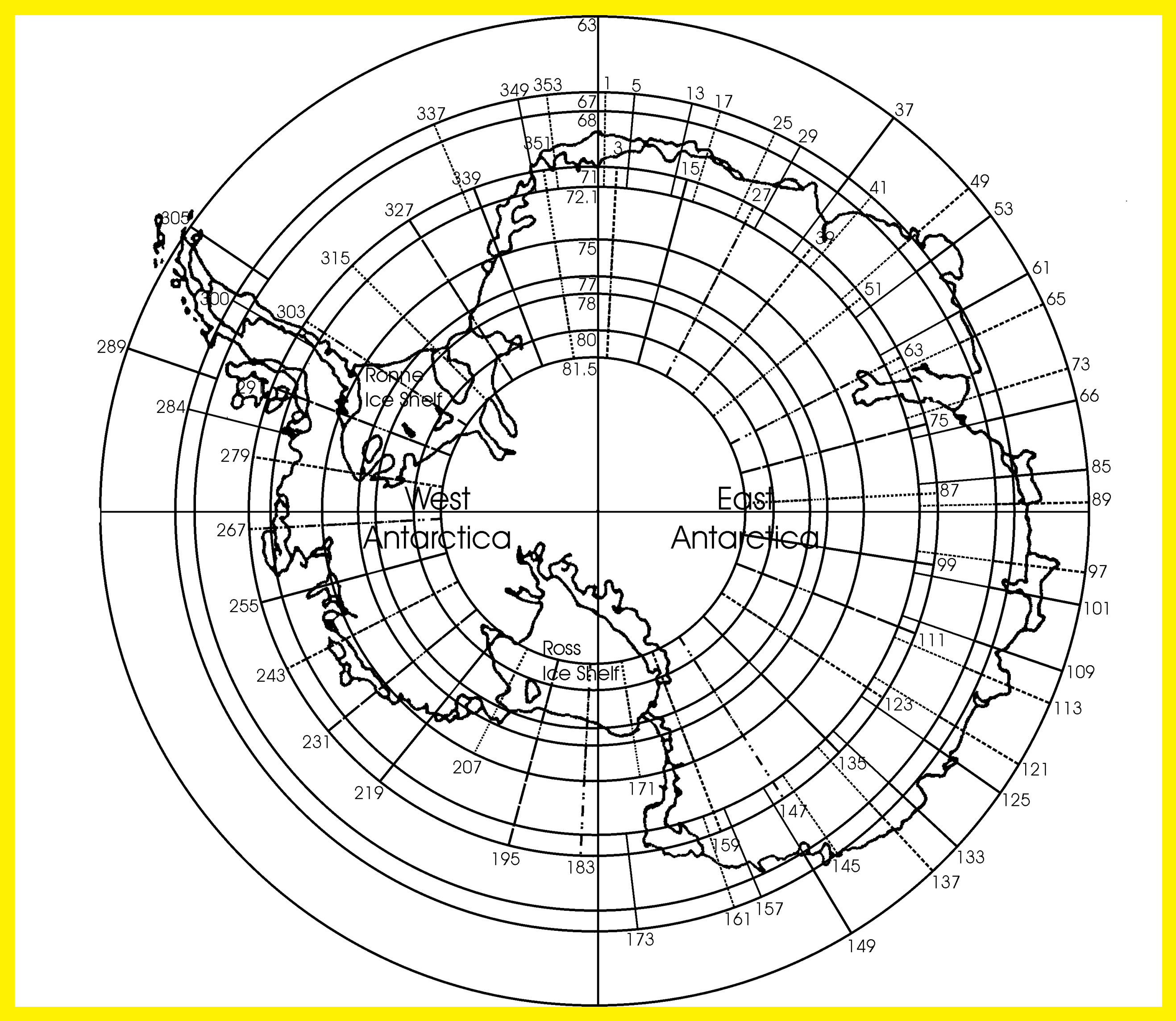
Altimeter Data Sources

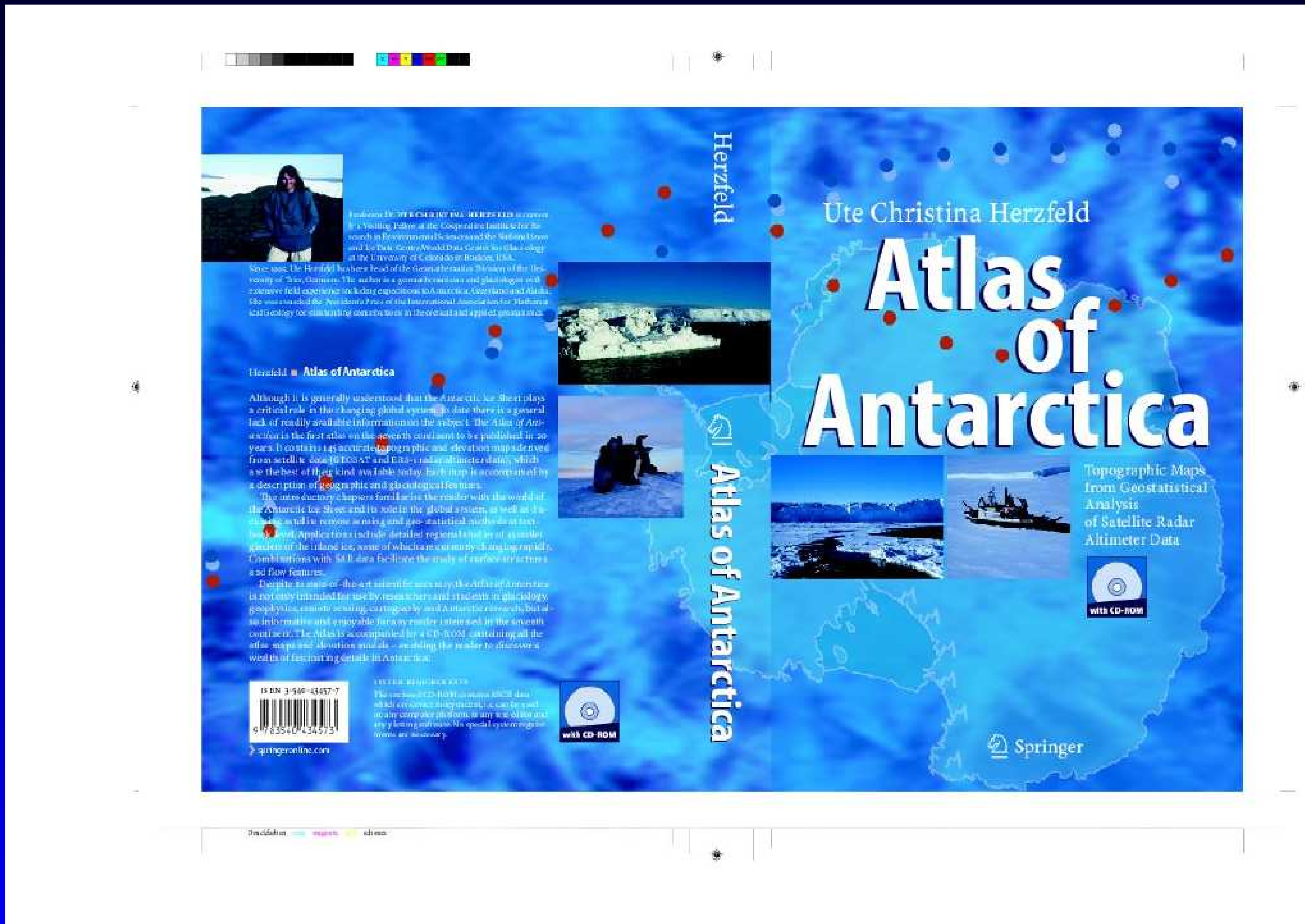
(a) ERS-1 Satellite Radar Altimeter Data (01 Feb–01 Aug 1995)

(b) ICESat GLAS Data (4 Oct–20 Nov 2003; Laser 2A; rel18)

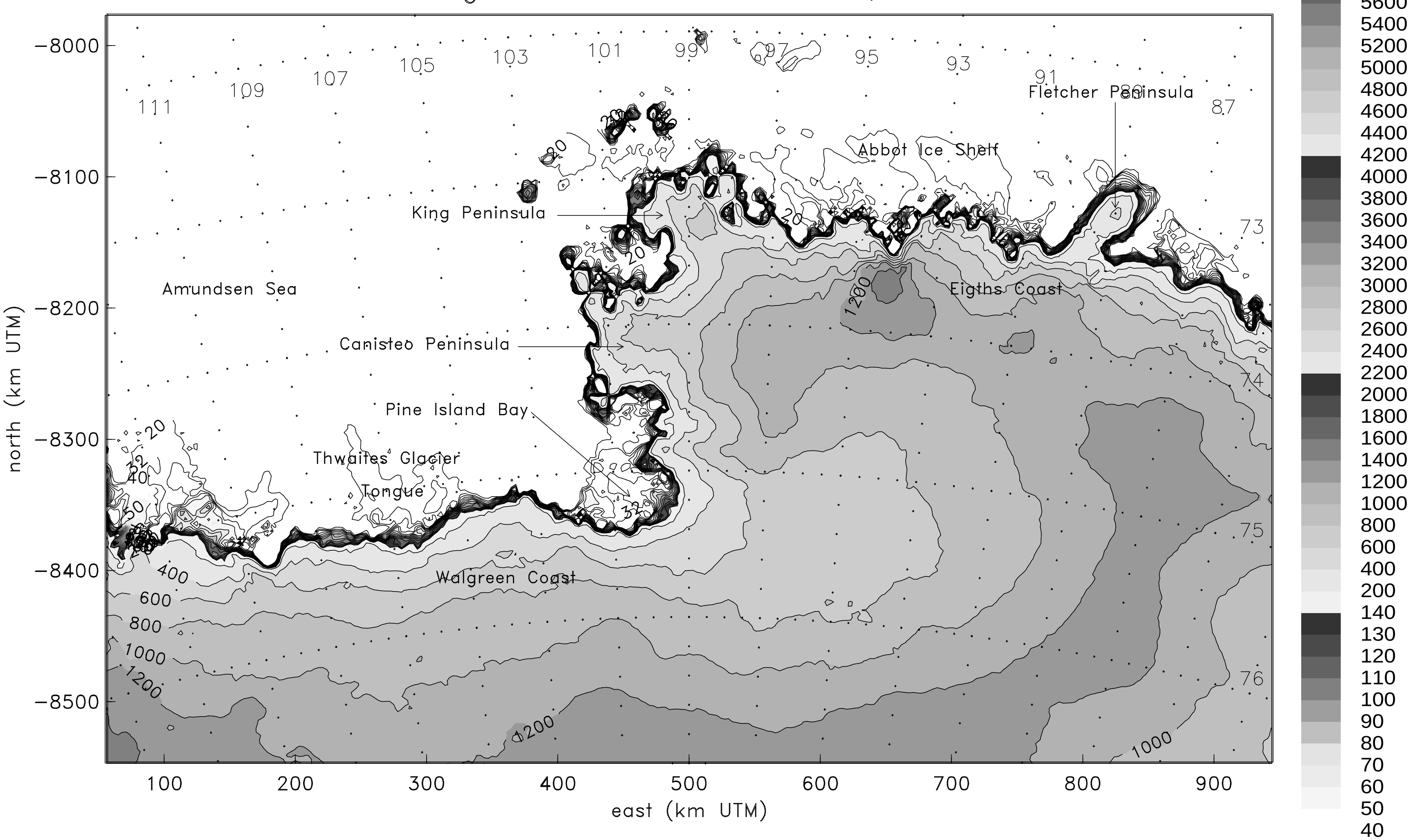
(c) ICESat GLAS Data (Oct/Nov 2006; Laser 3G; rel28)

Antarctic Atlas Mapping Scheme

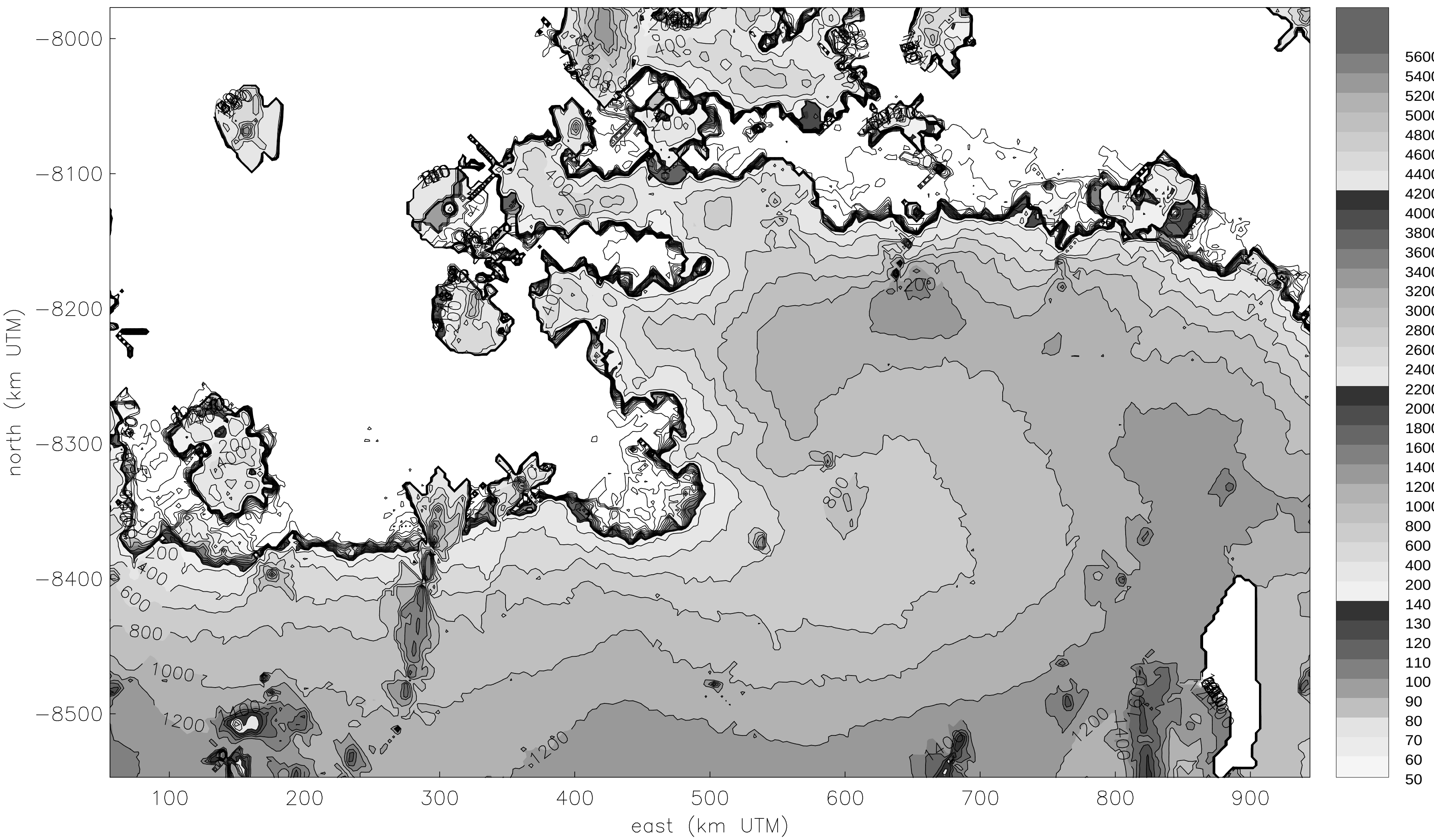



Ute Christina Herzfeld
Atlas of Antarctica
Topographic Maps from Geostatistical Analysis of Satellite Radar Altimeter Data
with CD-ROM
Springer
Herzfeld
Atlas of Antarctica
Herzfeld ■ Atlas of Antarctica
springeronline.com

Walgreen Coast – ERS-1 DATA, 1995



e243–279n71–77, WGS84, Gaussian variog., central mer. 261, slope corrected, scale 1:5000000, 980112

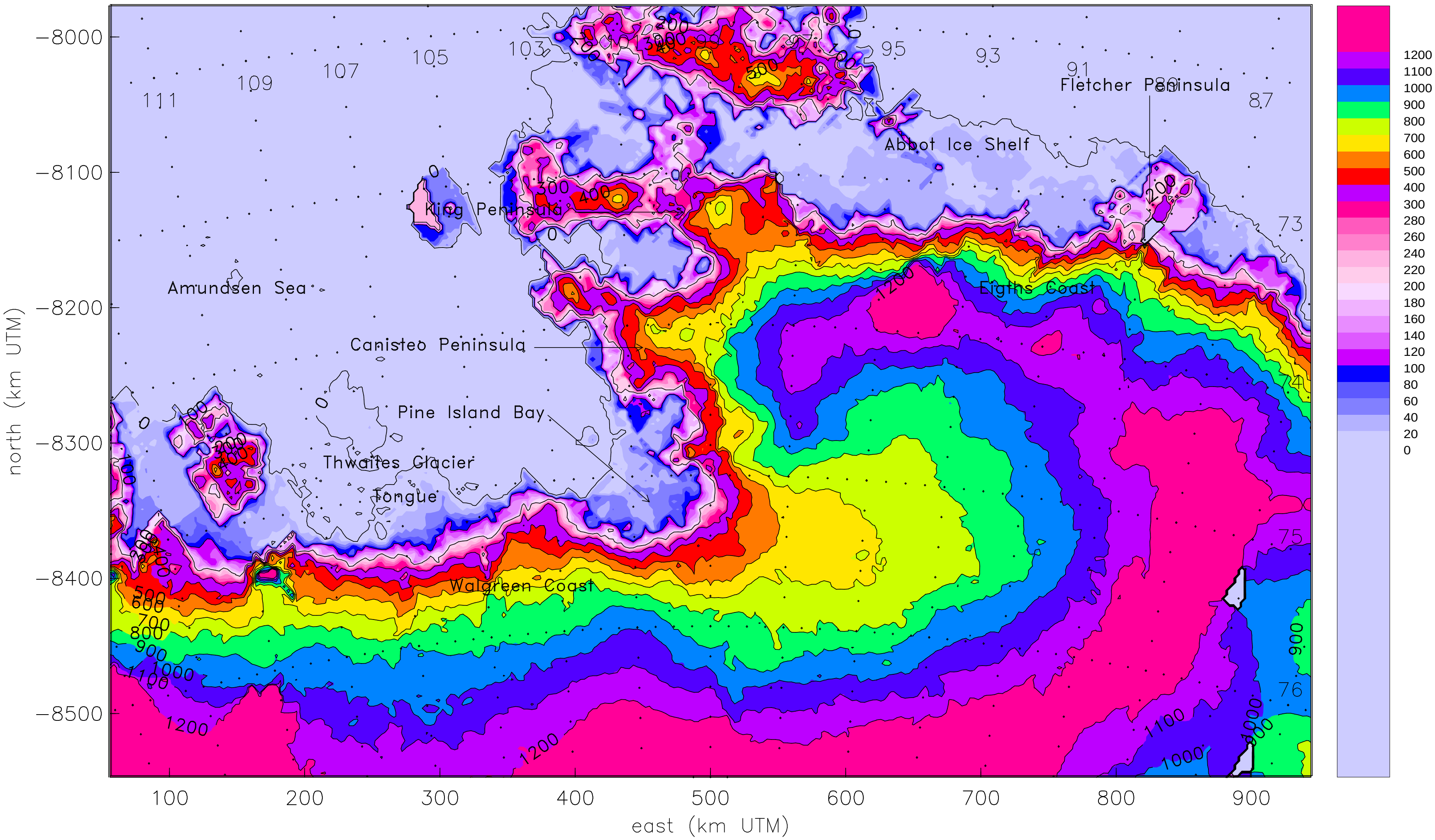


inuni.last33days.dat 20050225
297, 191, 1, 54500, −8548500, 0, 3000, 3000, 0, 1
30000.,16,10.,1,0,0,0,200.,8
1,1,0,0,0,33
0,0,0,'*'
gla06.last33days.trans
20050407
/data1/ws/pinegl/pigglas/rel18/gla06/last33days.totps

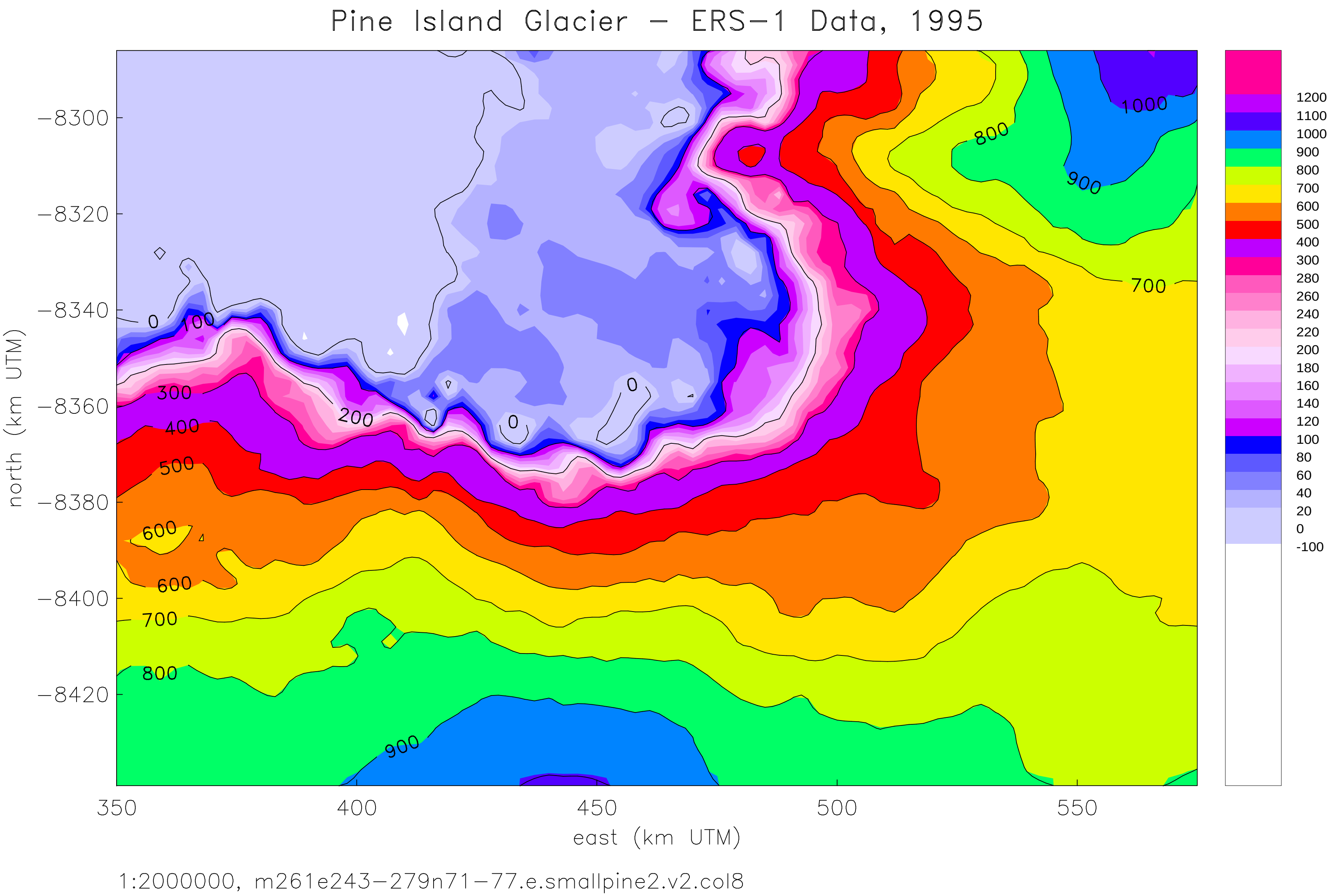
'*'
last33days.krg
last33days.dtm
last33days.est
'ICE ELEV',0,0,0,0,6
350,3100,3468.21,0,0,0,0,0,0,0,0,0,0,0,0,0,0

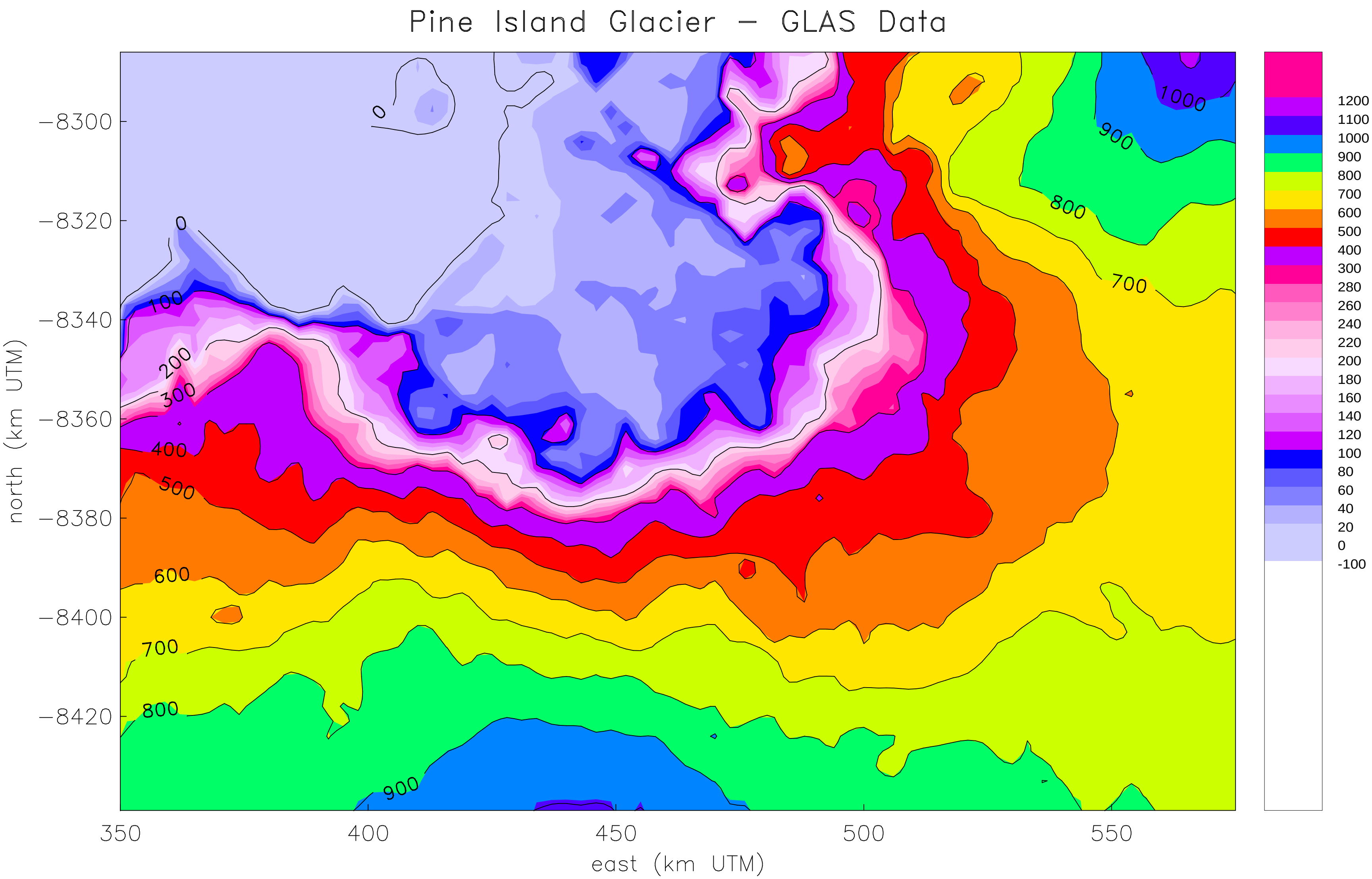
GLA06 (rel18, L2A, last33days) vario1(350,3450,6000m) search-rg 30km

Walgreen Coast – GLAS Data

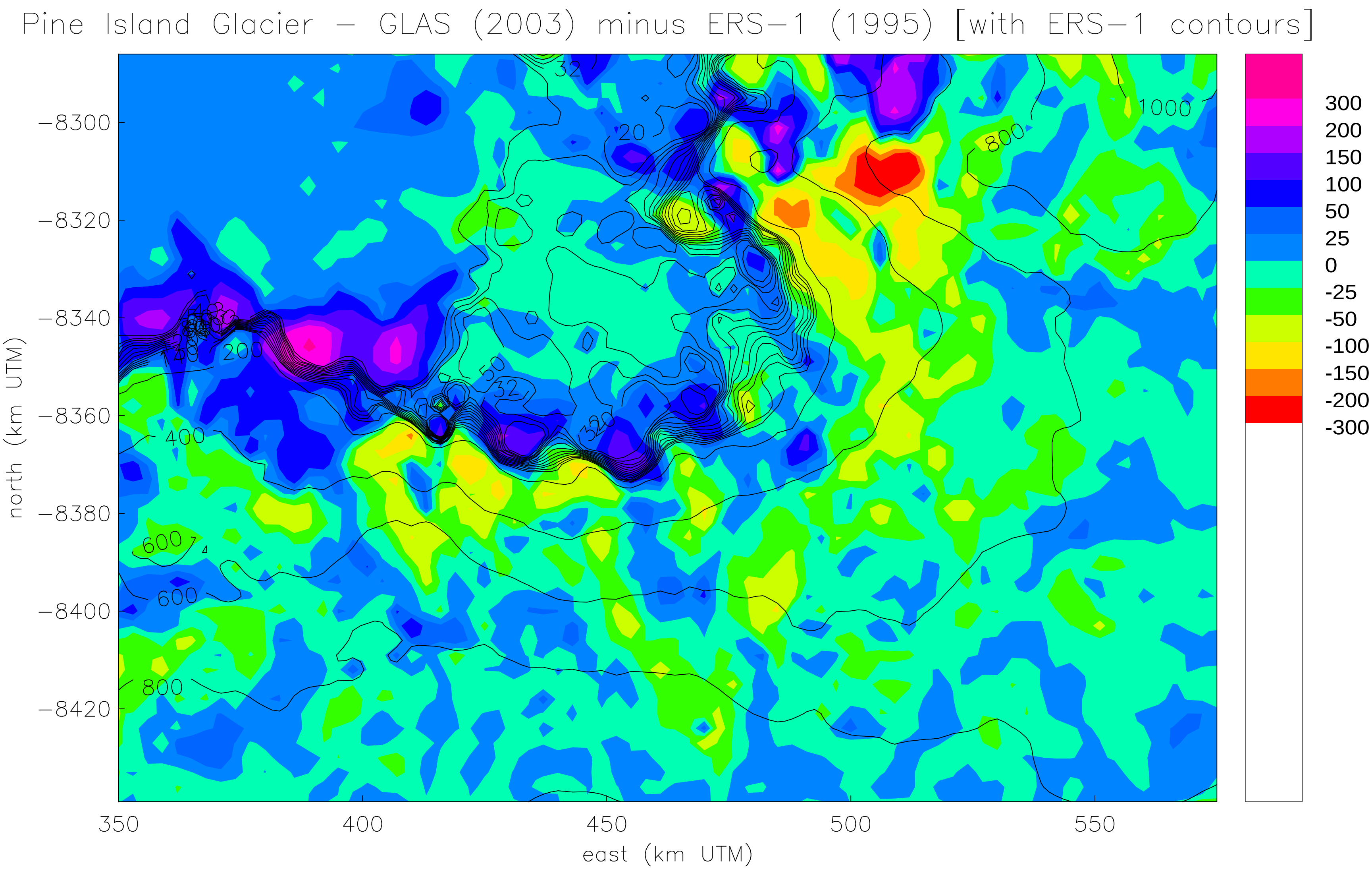


GLA06 Data, (Laser 2A, gain–crit, rel18), Oct/Nov 2003, vario(350,3450,6000m), search–rg 30km, 1:5000000, gla06.1.gain.0.col8


Pine Island Glacier – ERS–1 Data, 1995
north (km UTM)
−8300
−8320
−8340
−8360
−8380
−8400
−8420
east (km UTM)
350
400
450
500
550
0
100
200
300
400
500
600
700
800
900
1000
1200
1100
1000
900
800
700
600
500
400
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
-100
1:2000000, m261e243–279n71–77.e.smallpine2.v2.col8



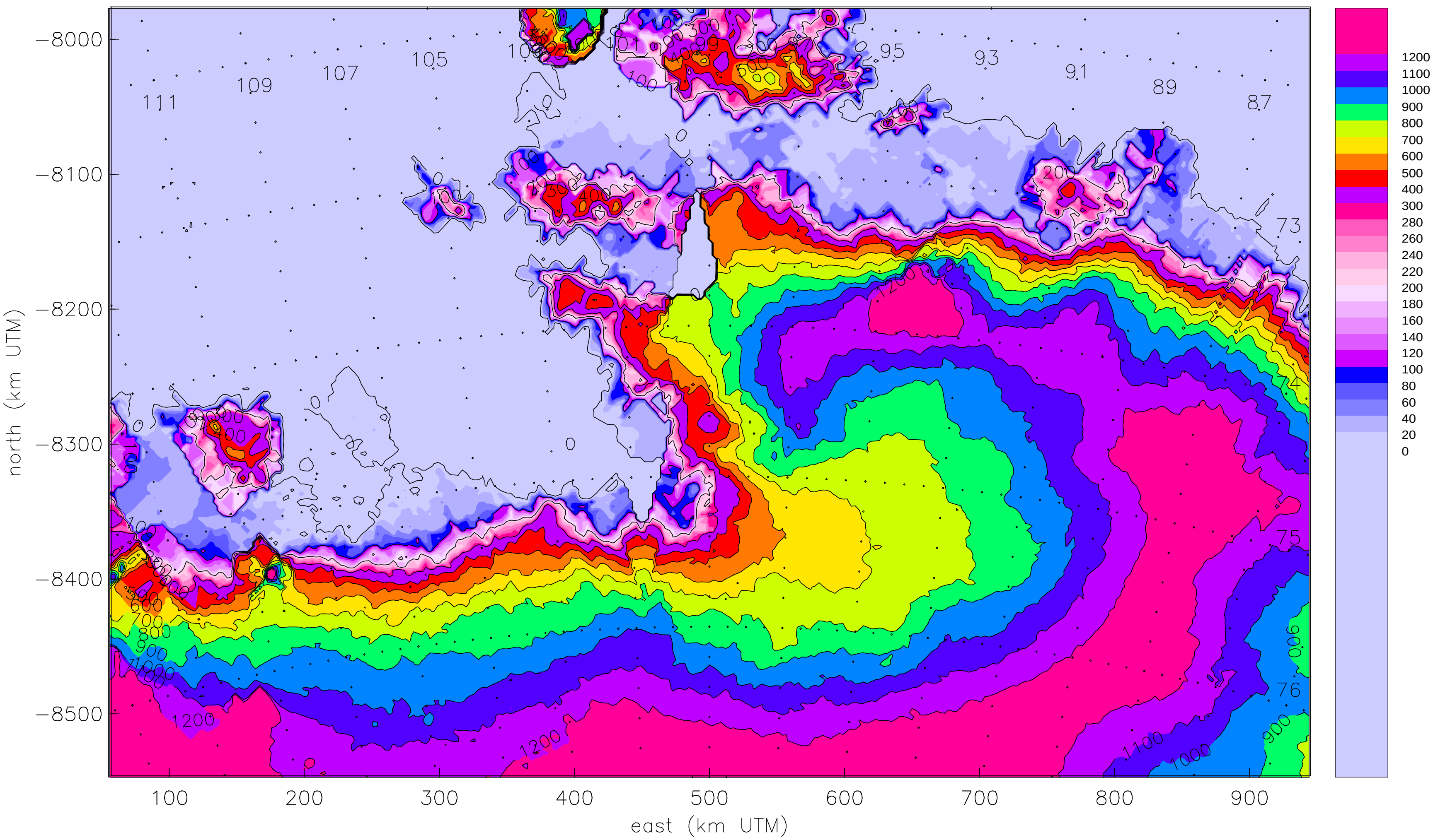
GLA06 Data, (Laser 2A, gain–crit, rel18), Oct/Nov 2003, vario(350,3450,6000m), search–rg 30km, 1:2000000, gla06.1.gain.smallpine2.v2.col8



scale 1:2000000 diff glasgain–ers1.wers1cont.smallpine2.col10.v2.totps 20050404

gla06.1.gain.smallpine2.0.dtm minus m261e243–279n71–77.e.smallpine2.0.dtm

Walgreen Coast, Antarctica:
GLA12 2006102512 (L3G, rel28)

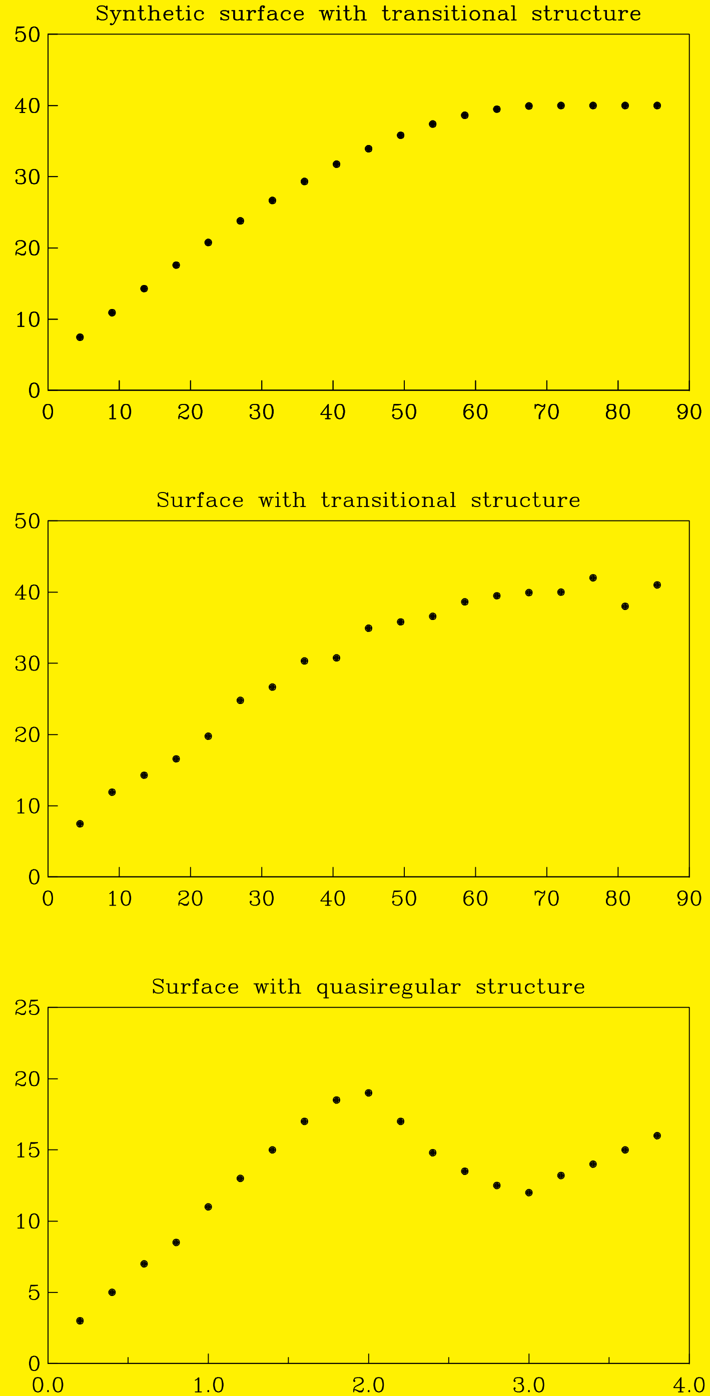


20080324
/data6/ws/pinegl2/glas/r2801/krig/GLA12−06102512−r2801.utm.0.col8.totps

Appendix

Geostatistical Classification —
Principles, Parameters, Feature Vectors, Classification Algorithms

Typical Experimental Variograms



Definition of Vario Functions

$V = \{(x, z) \text{ with } x = (x_1, x_2)\epsilon\mathcal{D} \text{ and } z = z(x)\} \subseteq \mathcal{R}^3$

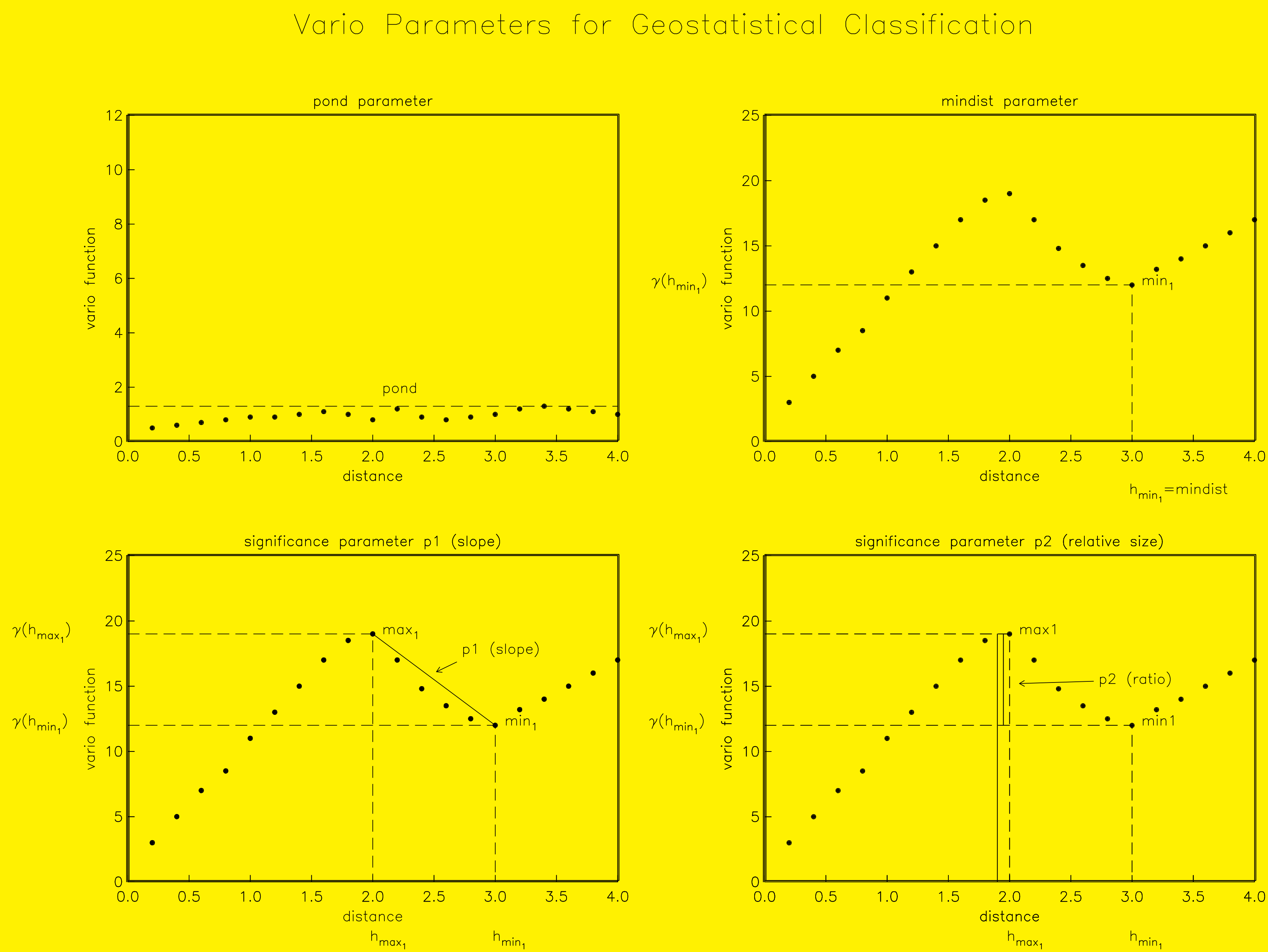
discrete-surface case or

$$V = \{(x, z) \text{ with } x\epsilon\mathcal{D} \text{ and } z = z(x)\} \subseteq \mathcal{R}^2$$

discrete-profile case
Define the *first-order vario function* v_1

$$v_1(h) = \frac{1}{2n}\sum_{i=1}^{n}[z(x_i) - z(x_i + h)]^2$$

with $(x_i, z(x_i)), (x_i + h, z(x_i + h))\epsilon\mathcal{D}$ and n the number of pairs separated by h.



Vario Parameters for Geostatistical Classification
pond parameter
pond
vario function
distance
mindist parameter
$\gamma(h_{min_1})$
min_1
h_{min_1}=mindist
significance parameter p1 (slope)
$\gamma(h_{max_1})$
max_1
p1 (slope)
h_{max_1}
h_{min_1}
significance parameter p2 (relative size)
max1
p2 (ratio)
min1

Geostatistical Classification Parameters

significance parameters:
slope parameter:

$$p1 = \frac{\gamma_{max_1} - \gamma_{min_1}}{h_{min_1} - h_{max_1}}$$

relative significance parameter:

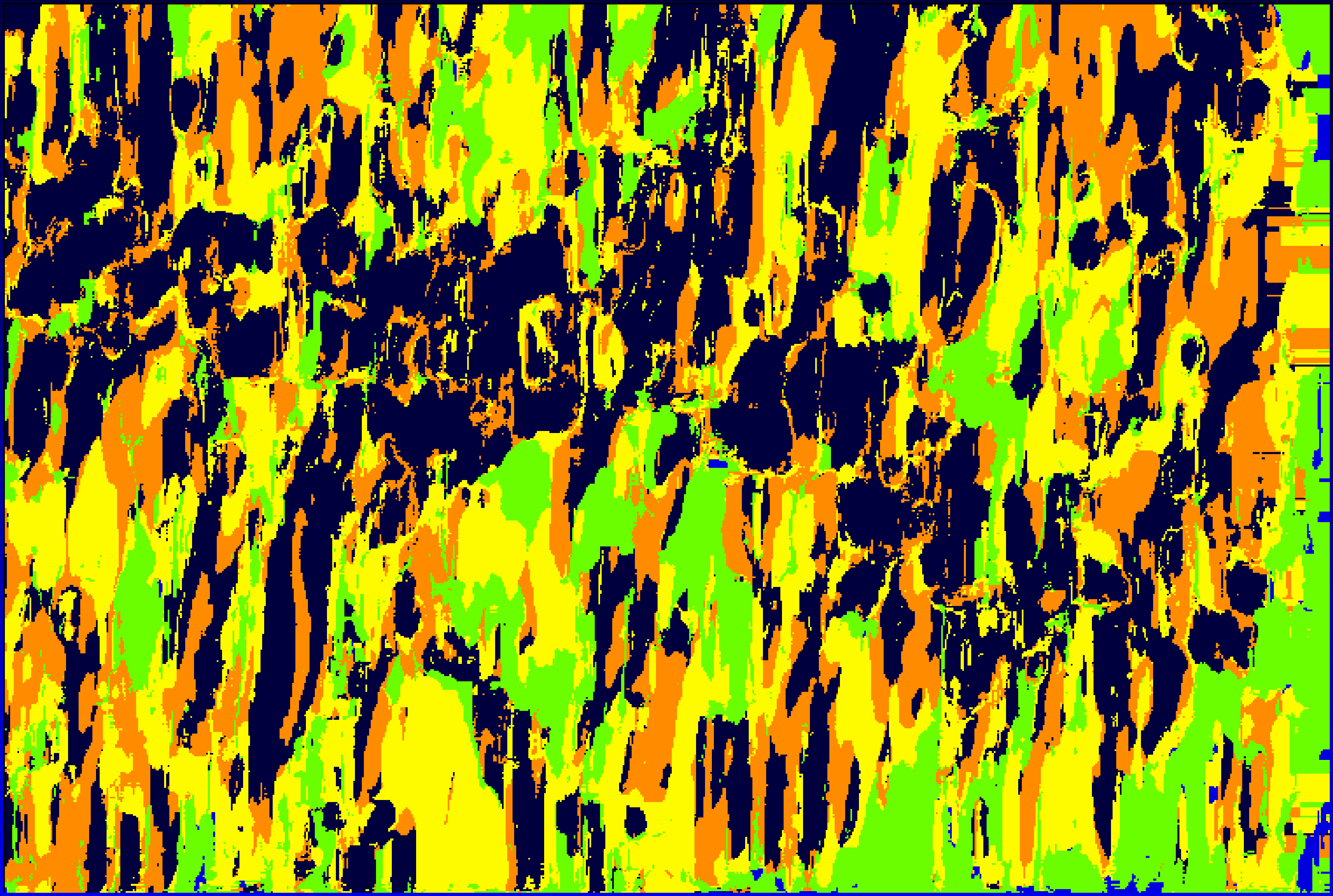
$$p2 = \frac{\gamma_{max_1} - \gamma_{min_1}}{\gamma_{max_1}}$$

pond – maximum vario value
mindist – distance to first min after first max

$$avgspac = \frac{1}{n} \sum_{i=1}^{n} \frac{1}{i} h_{min_i}$$

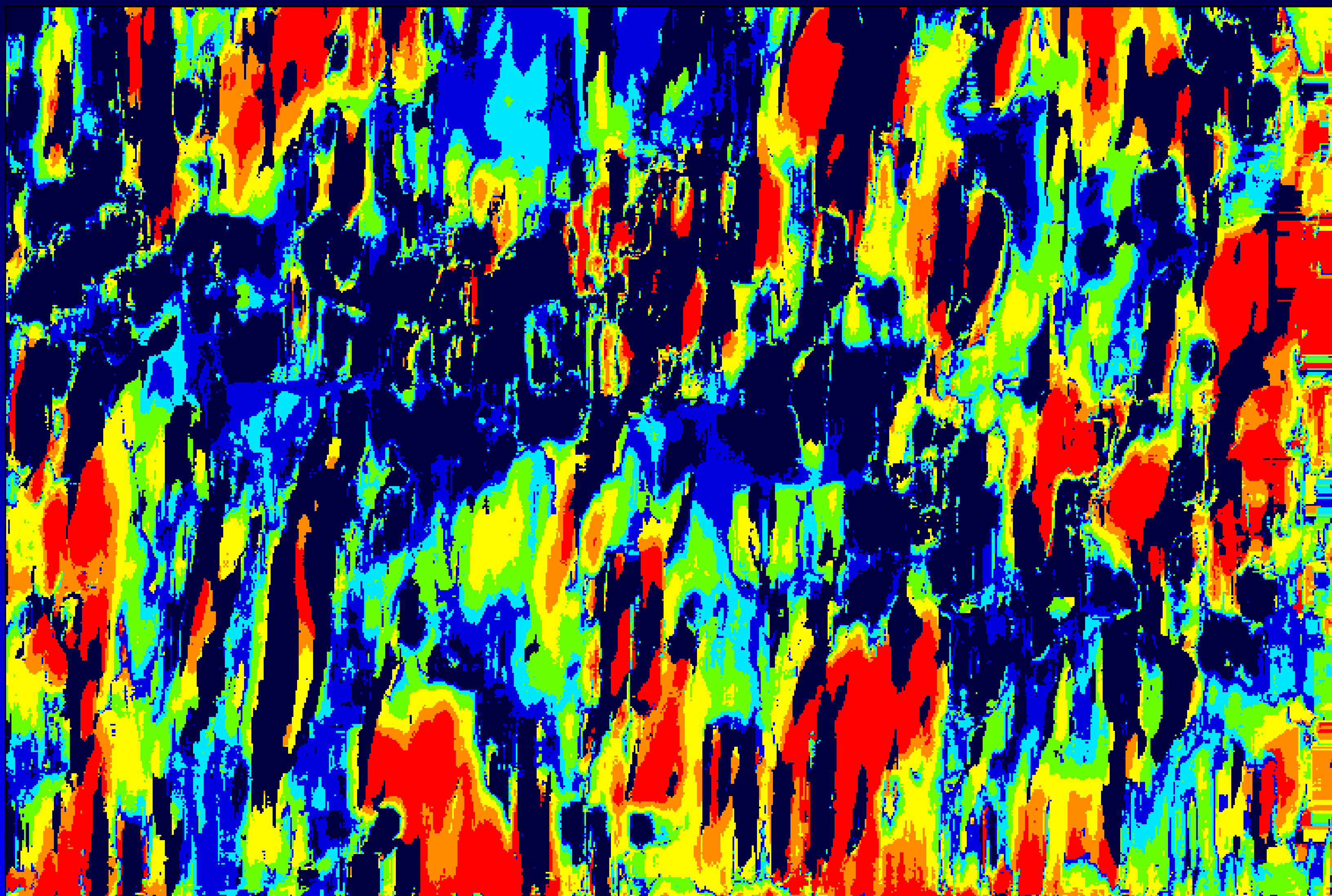
Geostatistical Seafloor Classification

Parameter $mindist$



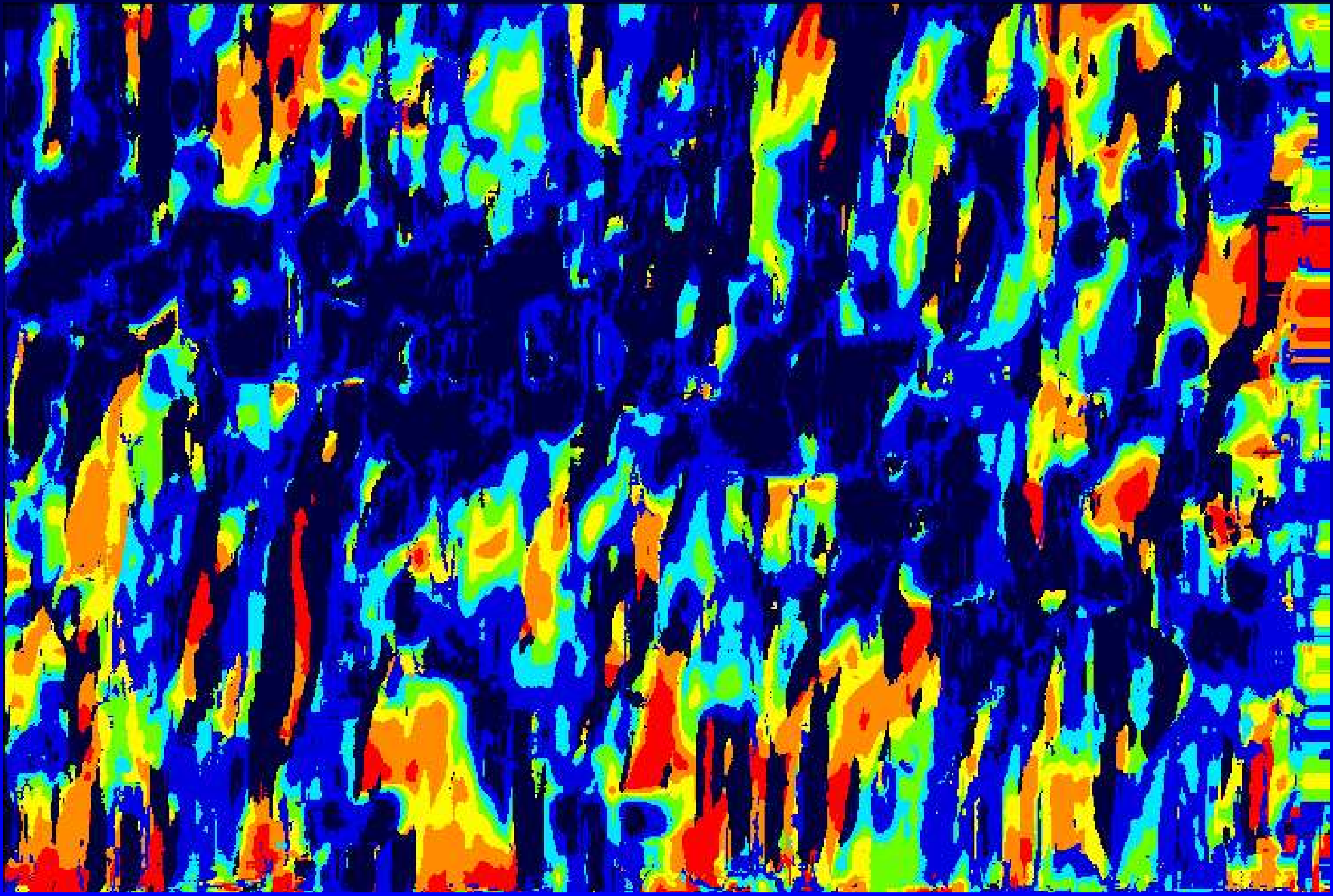
Geostatistical Seafloor Classification

Parameter $p1$:
significance of abyssal hill terrain (slope)



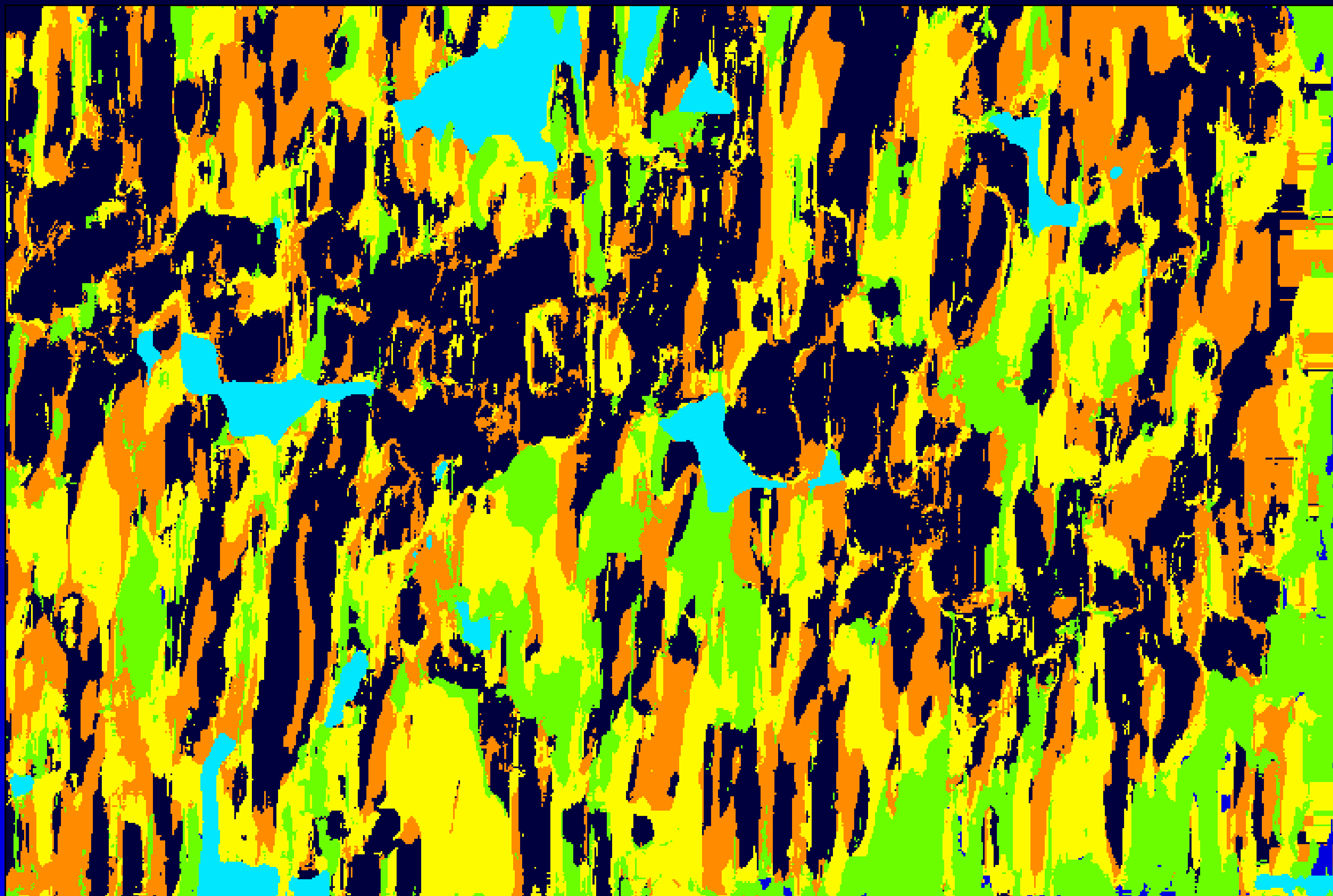
Geostatistical Seafloor Classification

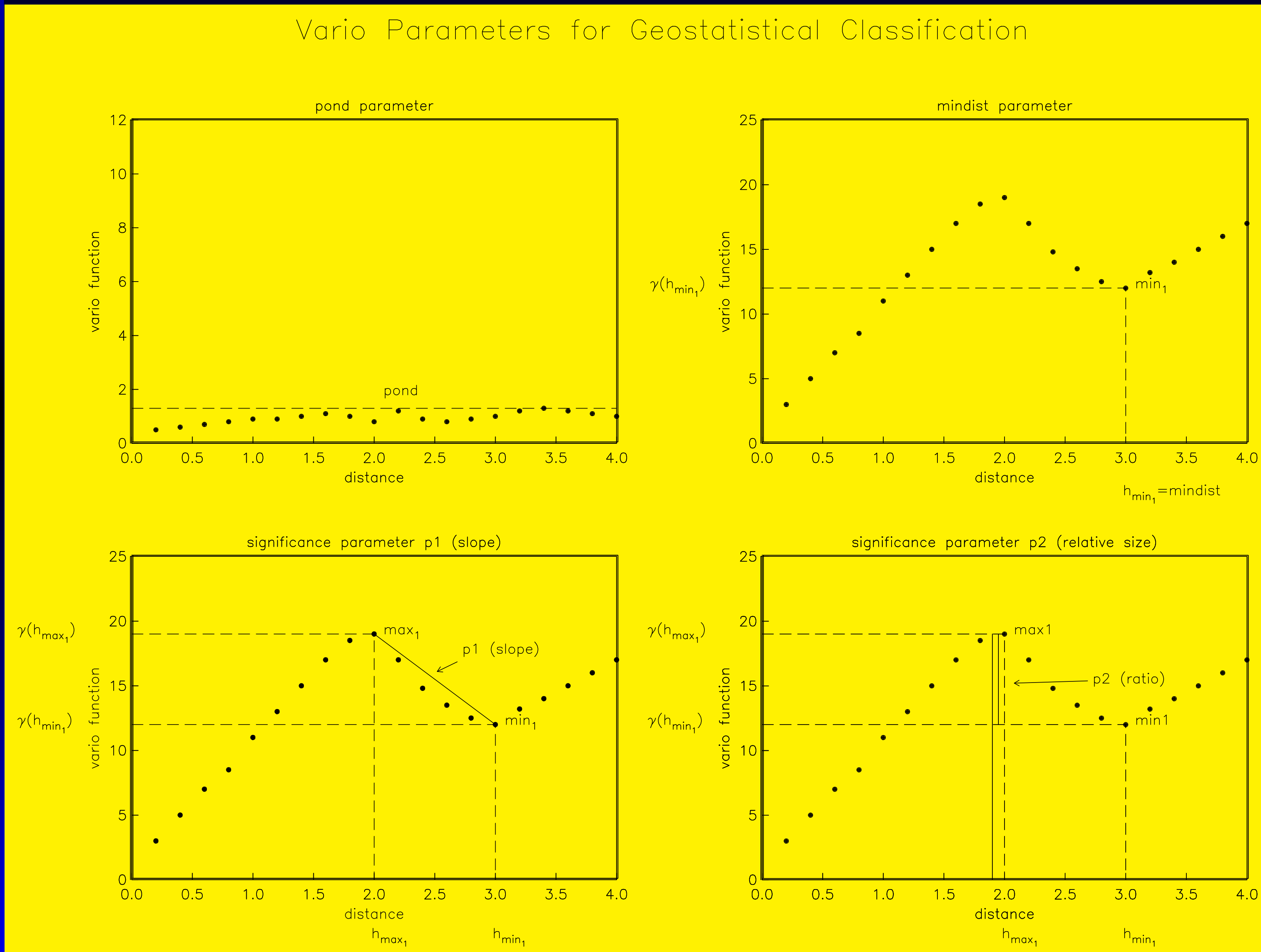
Parameter $p2$:
significance of abyssal hill terrain (relative size)



Geostatistical Seafloor Classification

Parameters $pond$ and $mindist$




Vario Parameters for Geostatistical Classification
pond parameter
vario function
distance
pond
mindist parameter
γ(h_min1)
min1
h_min1=mindist
significance parameter p1 (slope)
γ(h_max1)
γ(h_min1)
max1
p1 (slope)
min1
h_max1
h_min1
significance parameter p2 (relative size)
max1
p2 (ratio)
min1
h_max1
h_min1