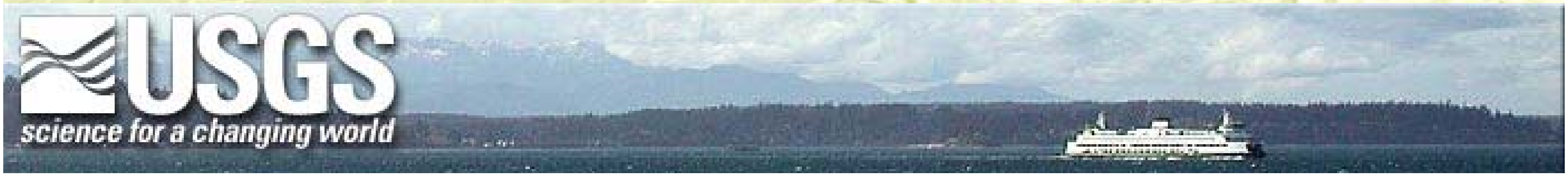
New Tools in Process-Based Analysis of Lidar Topographic Data, June 1-2, 2010, Boulder, CO

Remotely sensed topography used to map earth history

Ralph Haugerud, U.S. Geological Survey
c/o Dept Earth & Space Sciences, University of Washington
Seattle, Washington

Special thanks to colleagues past and present in the Puget Sound Lidar Consortium, including David Harding (NASA), Jerry Harless (PSRC), Phyllis Mann (Kitsap County), Diana Martinez (PSRC), and Craig Weaver (USGS)



Outline

1. Remotely sensed

   Airborne lidar is swath mapping, pointing error dominates. Samples, not a complete description

2. Topography

   Continuous, single-valued, mineral, non-anthropogenic? Not well defined at m and cm scale

3. Used

   Poor usability and incompleteness are more common problems with lidar data than lack of accuracy

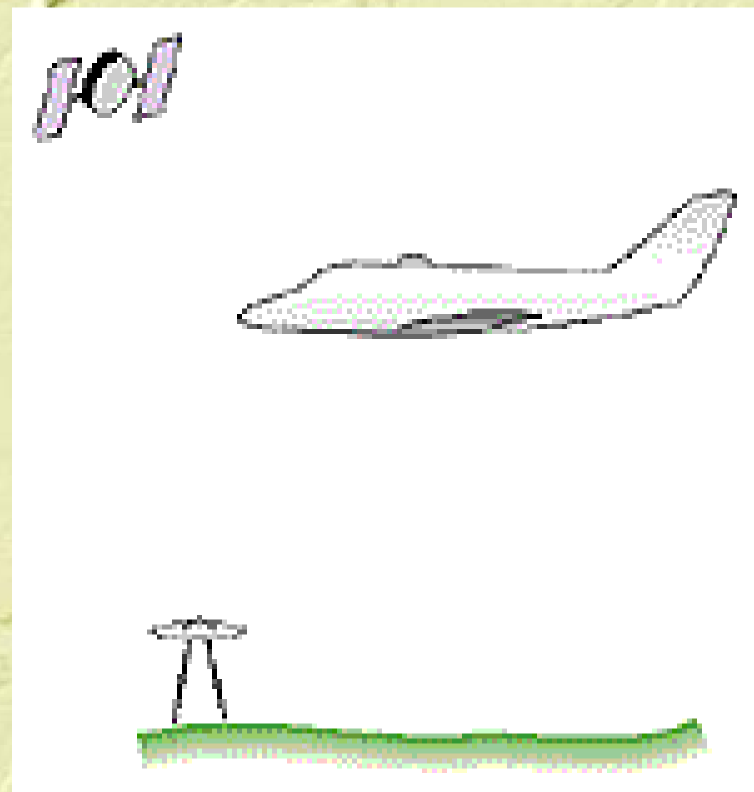
4. To map

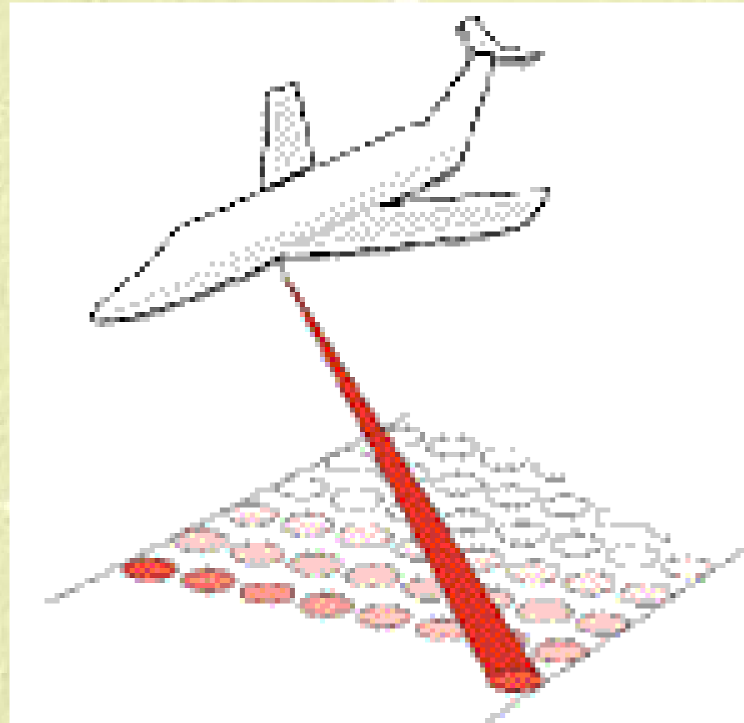
   Map = explore, inventory, explain. Map units = f(mappability, time, process). Calculate the right image

5. Earth history

   Retreat of the last ice sheet from the Salish Lowland. Outwash flats are strain markers with which to discern Holocene tectonism

1. Remotely sensed





Lidar is complex technology and it's worth thinking a little about how it works

graphic courtesy Natural Resources Canada

To make a lidar DEM

- Position & orient aircraft with GPS and IMU
- Scan landscape with laser rangefinder
- Calibrate position, orientation, and range measurements (*GCP match*, *swath-swath match*); reduce measurements to ground coordinates. Iterate
- Identify ground points
- Create surface model from ground points

Each step contributes to the accuracy of lidar DEM

Topics: measurement reproducibility, DEM reproducibility, adequacy of ground-point sample

Accuracy of lidar point measurements

What the vendor can be held responsible for

Evaluation requires abundant, expensive GCPs

Industry standards focus on vertical accuracy of points on near-horizontal, near-bare surfaces

As a substitute, look at

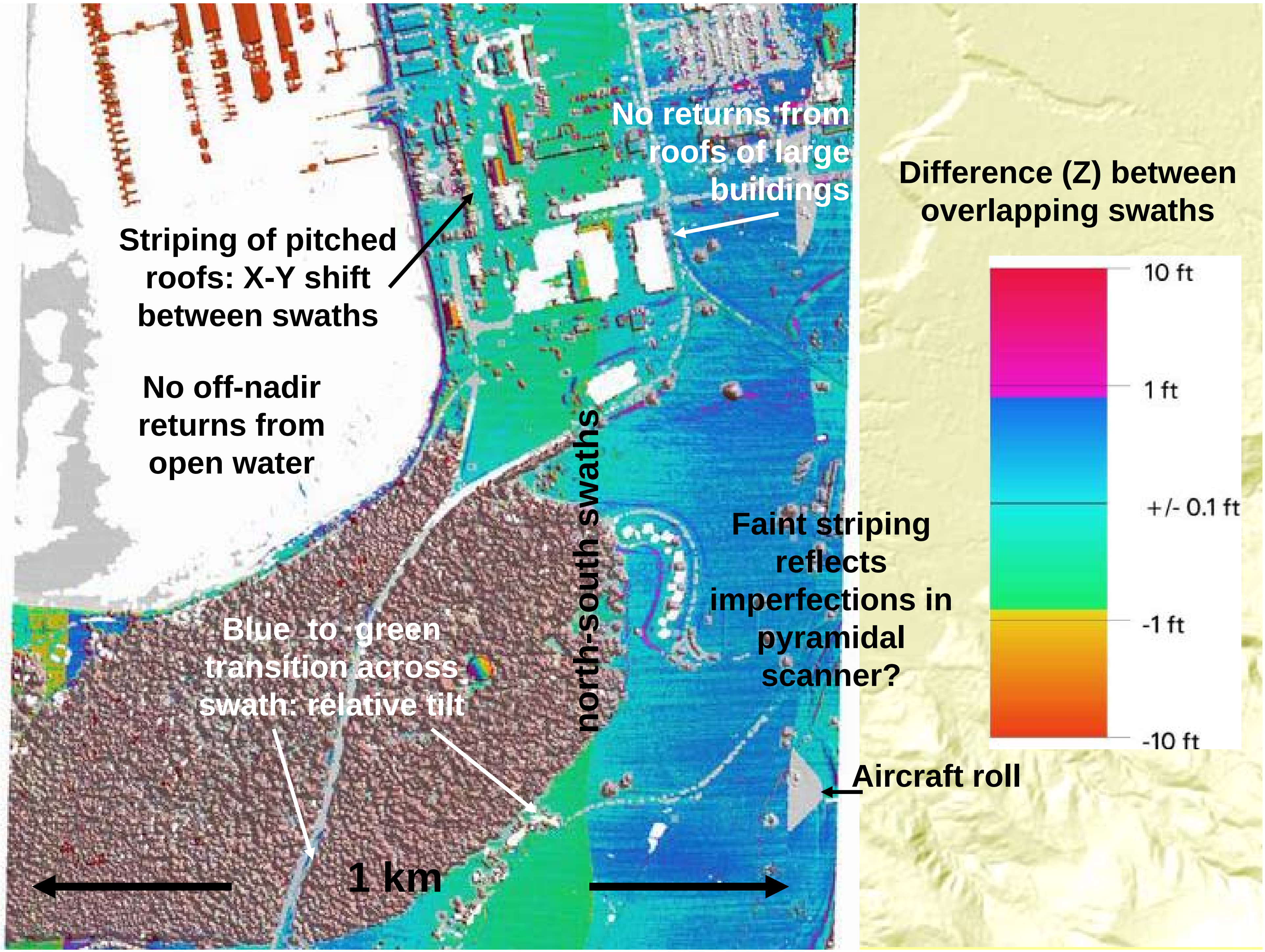
- Reproducibility (consistency) of point positions

  Can be cheaply evaluated from swath overlaps

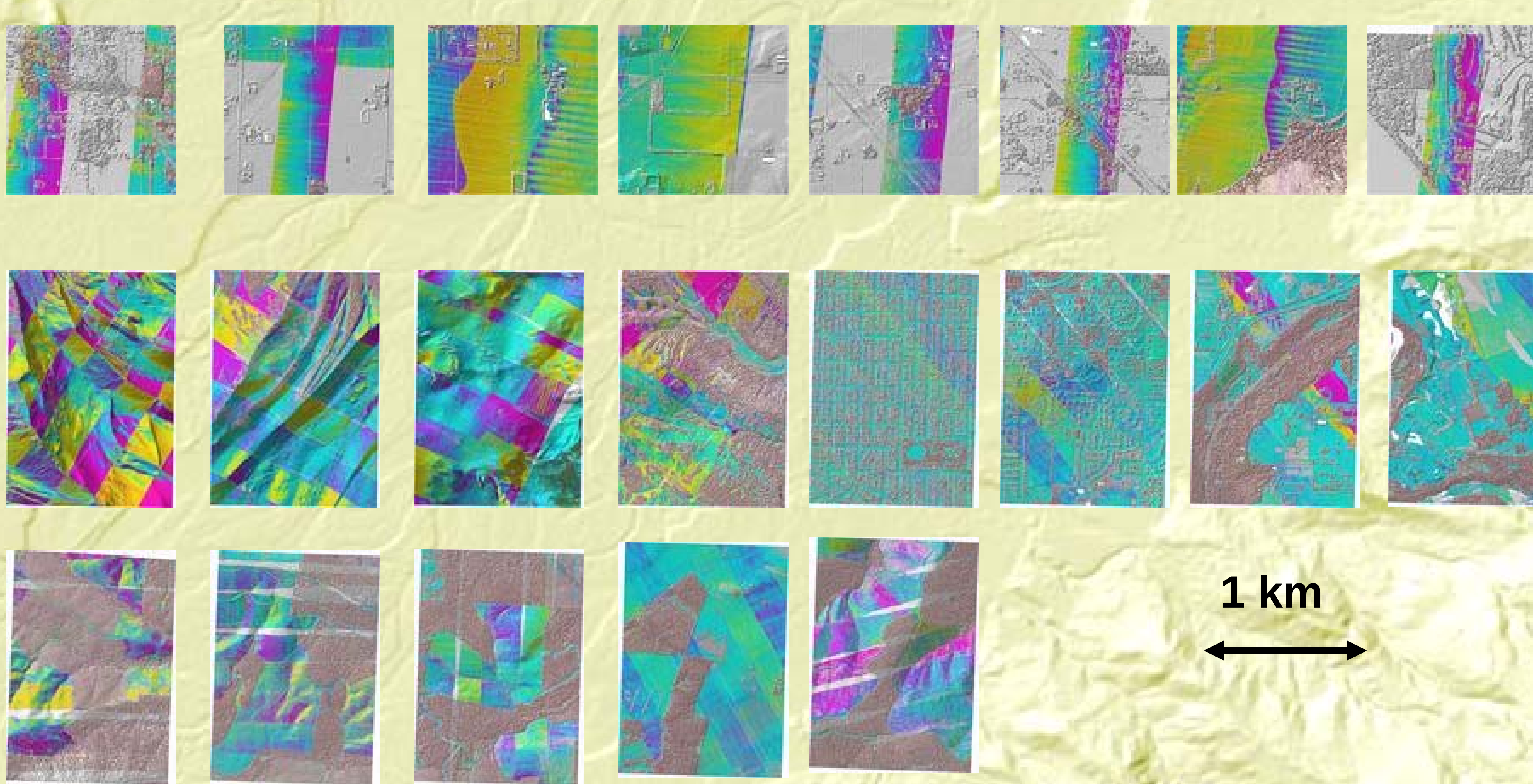
  Provides lower bound on measurement accuracy

CONSISTENCY analysis

- Start with tile of multiple-swath data
- Sort on time. Split into swaths at time breaks. For each swath
  - Identify data areas
  - Build surface (1^{st}-return points $\rightarrow$ TIN $\rightarrow$ lattice)
- Subtract swath surfaces, spatially merge differences
- Calculate local curvature to identify smooth areas where interpolation is valid
- Make image
  - Saturated color = smooth area with overlap
  - Unsaturated color = rough area with overlap
  - Gray = no overlap
  - White = no data


No returns from roofs of large buildings
Difference (Z) between overlapping swaths
Striping of pitched roofs: X-Y shift between swaths
No off-nadir returns from open water
north-south swaths
10 ft
1 ft
+/- 0.1 ft
-1 ft
-10 ft
Faint striping reflects imperfections in pyramidal scanner?
Blue to green transition across swath: relative tilt
Aircraft roll
1 km

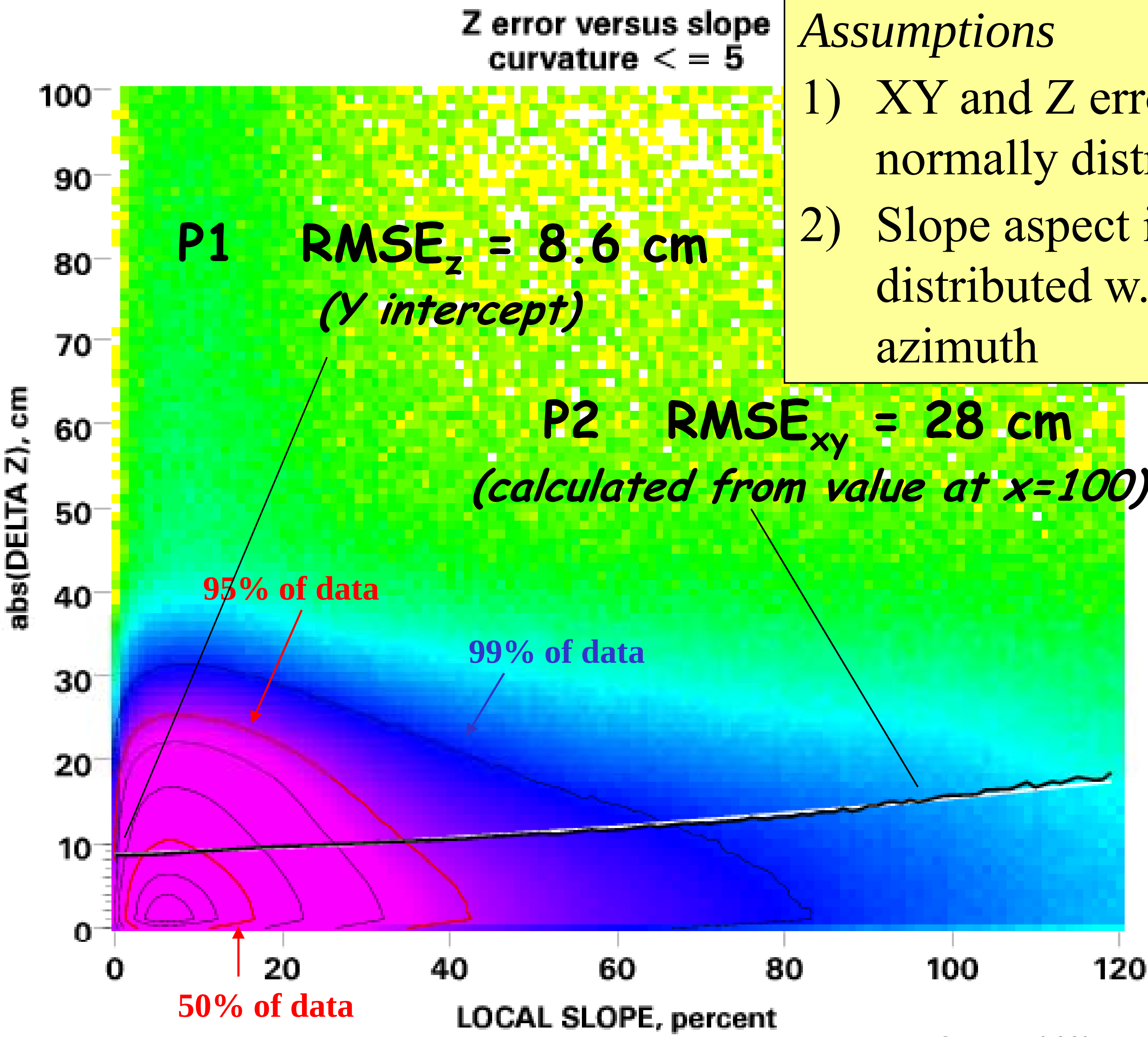
The dominant source of error in most airborne lidar data is swath-related



- Larger ΔZ on steeper slopes implies XY mismatch larger than Z mismatch
- This is the norm
- Conclusion: pointing is bigger problem than positioning

Assumptions

1) XY and Z errors are normally distributed
2) Slope aspect is uniformly distributed w.r.t. XY error azimuth



n ≈ 25 million

quadrangles, 2 pulse/m^2

Color = data density

wiggly black line: RMS Y for each X

smooth white line: least-squares best fit quadratic

Corollaries to dominance of swath-related pointing error

- To improve accuracy, improve pointing calibration
- Local averaging to reduce absolute errors is ineffective
- For best shapes in open areas, use single-swath data
- In general, denser data = more accurate data
  - Calibration involves less XY interpolation, thus is more precise
  - Denser data = lower flying height = less XY error for given pointing error

Also, denser datasets commonly have smaller fraction of ground-point classification errors

Accuracy of point-based DEM

What we care about

Evaluation requires abundant, expensive GCPs

As a substitute, look at:

- Reproducibility (consistency) of DEM

  Can be cheaply estimated from swath overlaps

  Provides lower bound on DEM accuracy

- Quality of the ground-point array

  Quantify how well ground points (assumed to be accurate) characterize topography

To make bare-earth DEM:

1) Measure XYZ of points
2) Classify points as ground or not-ground
3) Interpolate ground points to continuous surface

DEM error $\approx$

$$\left[\ (\text{measurement error})^2 + (\text{classification error})^2 + (\text{interpolation error})^2\ \right]^{1/2}$$

small, ≤10 cm

may be large in forested terrain

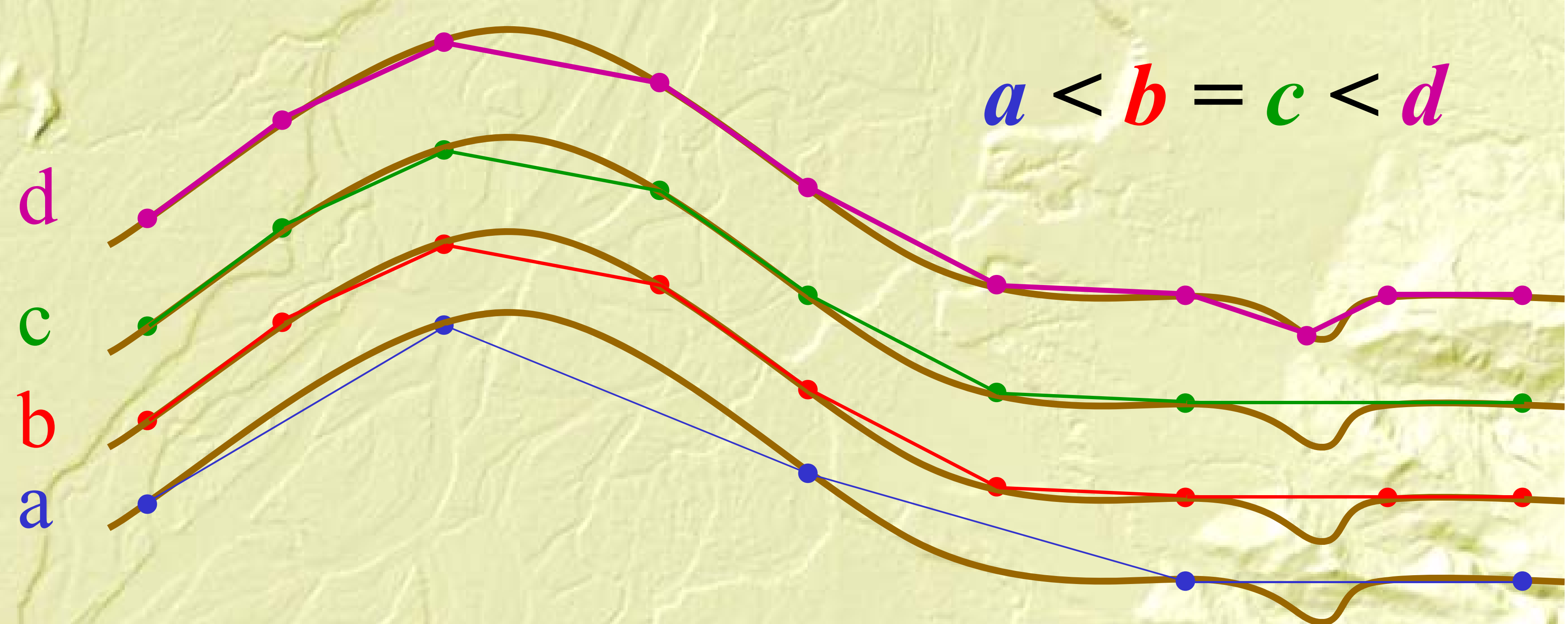
ditto

Rule of thumb:

internal DEM reproducibility =

~2 x Z measurement reproducibility

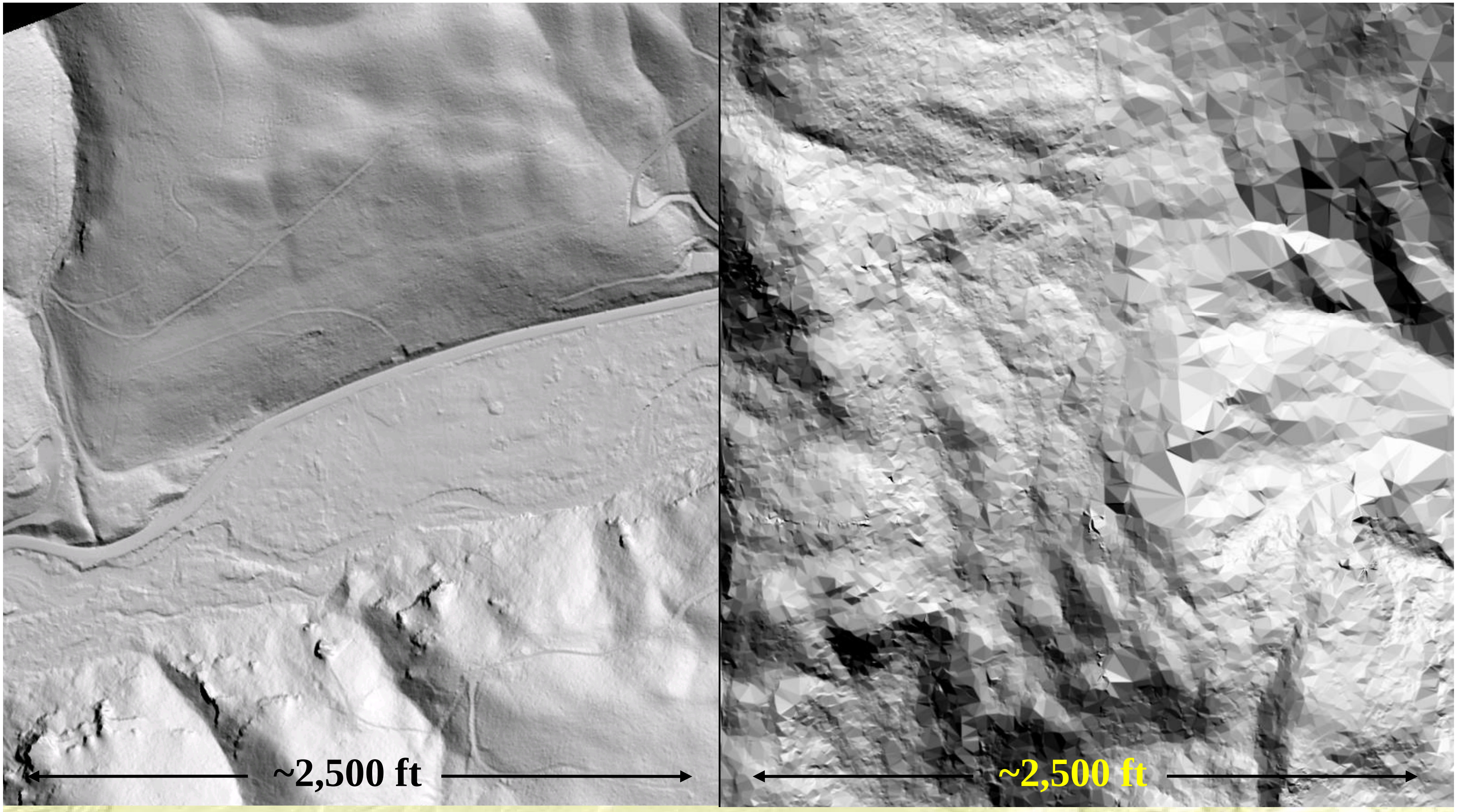
How well do ground points sample Earth's surface?



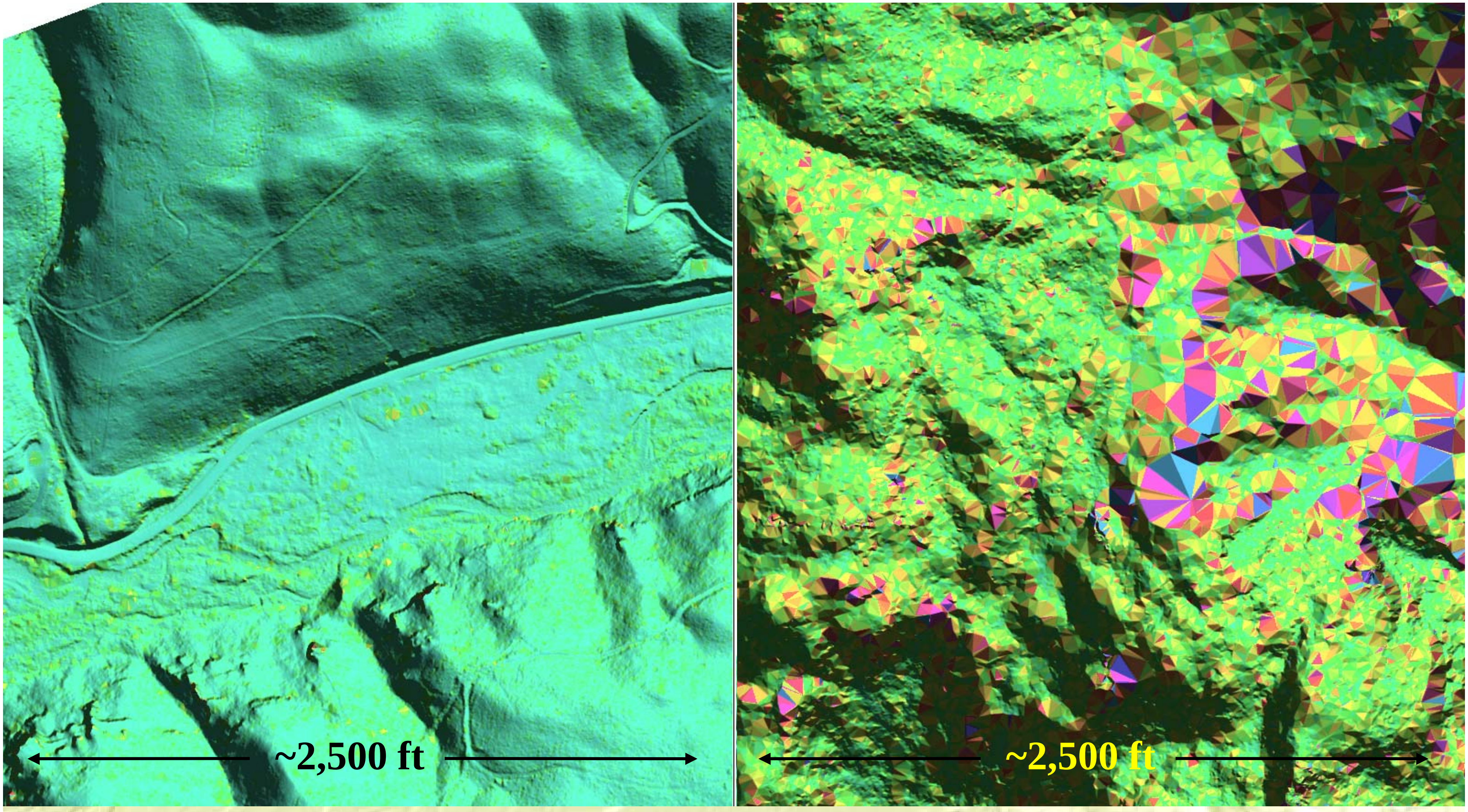
Without knowledge of the true surface, likely estimates of sample quality are:

interfacial angle (closer to 180 = better)

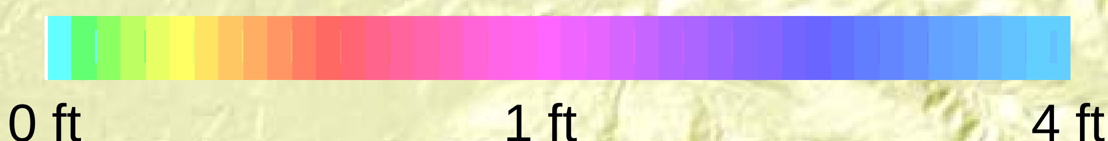
edge length (smaller = better)



~6 pulse/m², leaf off		~1 pulse/m², leaf on	
median edge length **3.1 ft**	median i.f. angle **176.4º**	median edge length **14.8 ft**	median i.f. angle **170.7º**
95% edge length **8.7 ft**	95% i.f. angle **165.8º**	95% edge length **68.6 ft**	95% i.f. angle **142.8º**



Images colored by estimated per-facet average interpolation error



2. Topography n. The 2½-D shape of the Earth's surface. Once commonly depicted with contours, now commonly depicted and analyzed as a raster.

Current practices suggest to me that we assume topography is (more or less):

- Continuous & differentiable
- Single-valued
- Mineral
- Non-anthropogenic

3. Used

Despite our preoccupation with accuracy, most problems with lidar data stem from lack of *usability* and failure to be *complete*.

Usable data have

- Report of Survey
- Formal metadata
- Correct and correctly labeled spatial reference framework
- Consistent file names and file formats
- Workable tiling scheme *(can calculate names of adjoining tiles)*
- Consistent calibration

Usable data have

- Consistency between data layers
- No unnecessary artifacts in surface models

Complete data have

- No gaps
- Adequate data density
- Adequate swath overlap

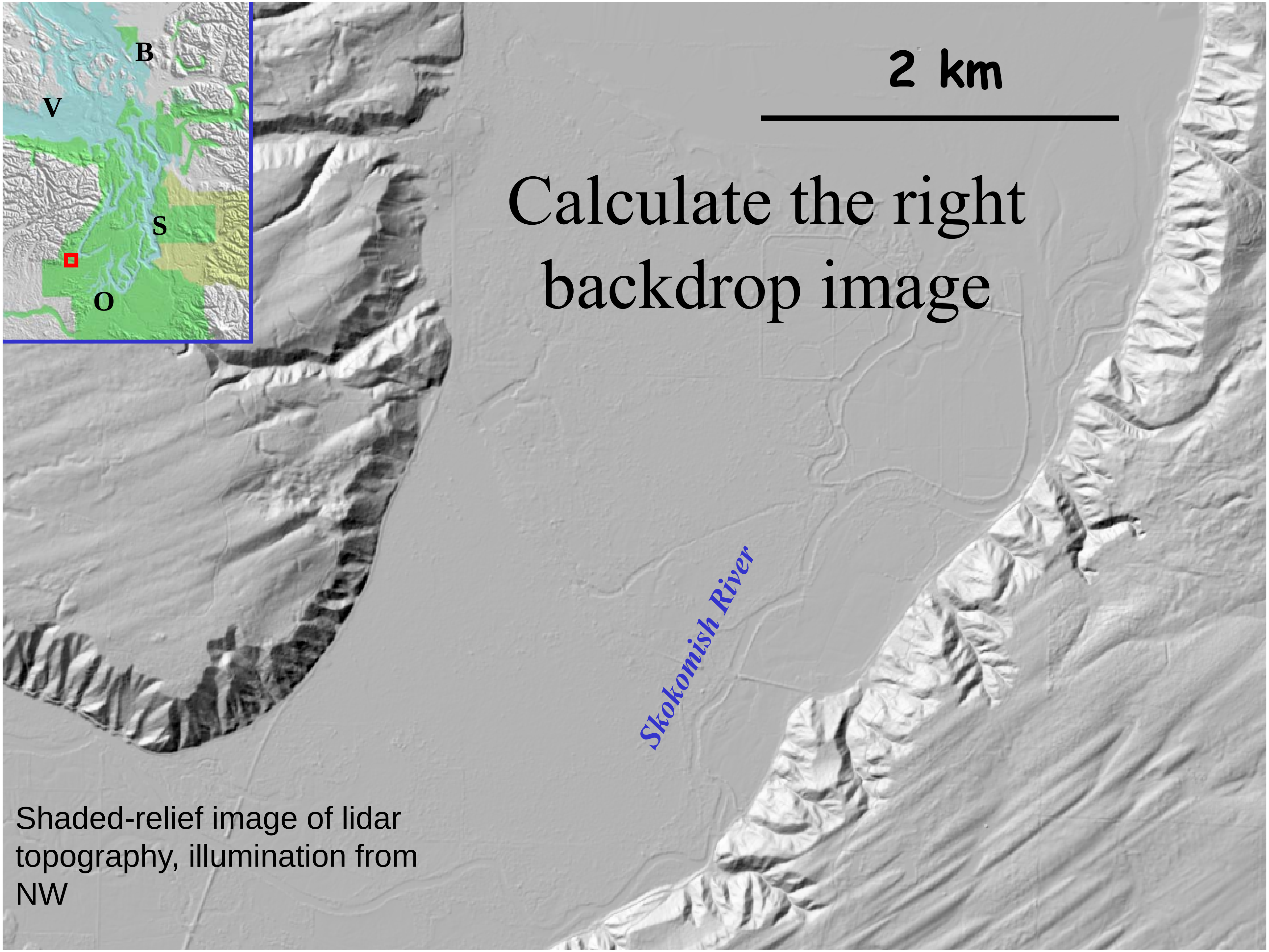
These are what we pay for

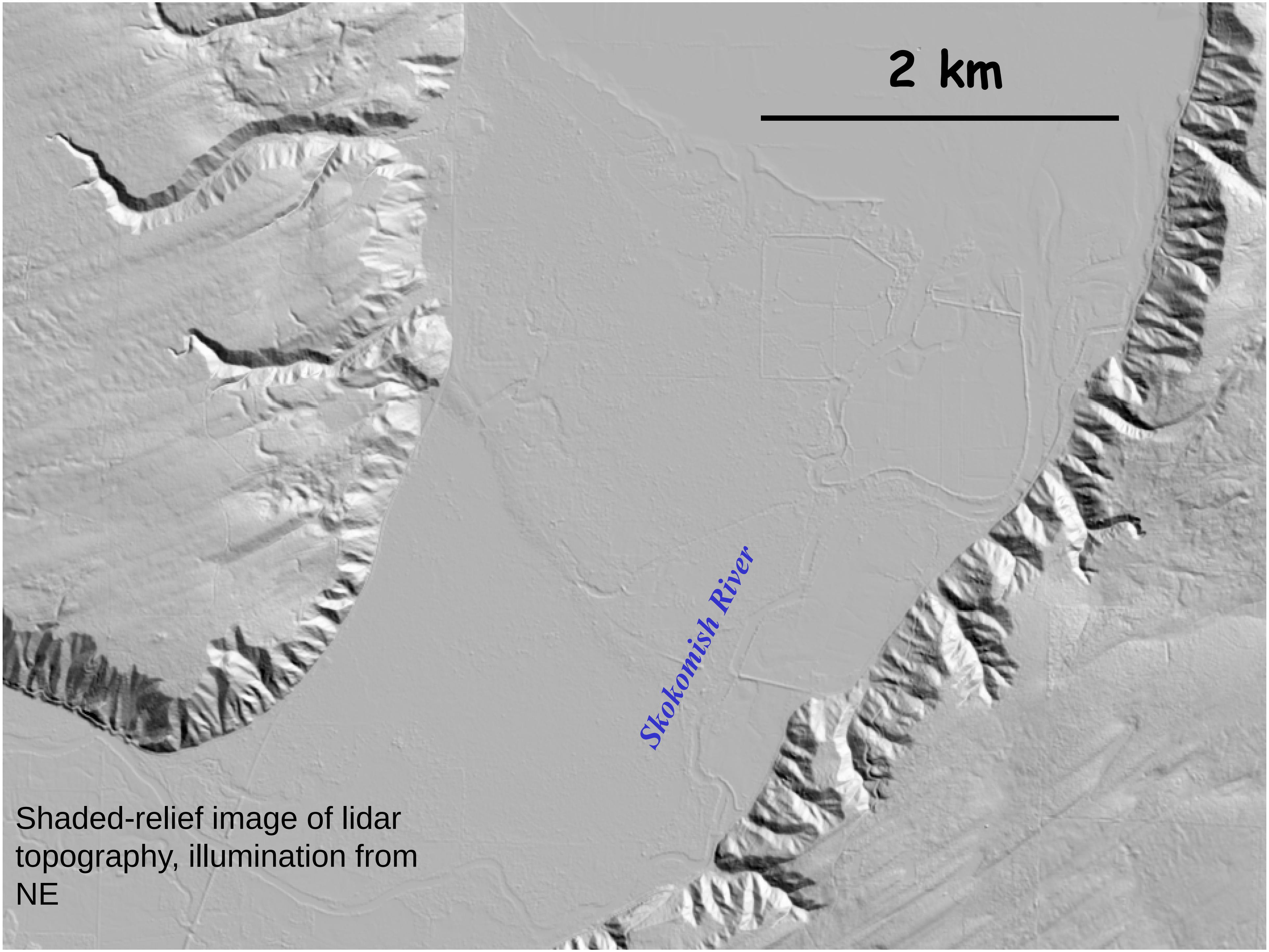
4. To map

- Map is a verb: an activity that includes exploration, inventory, and explanation
- Geomorphic mapping:
  - Parse landscape into geomorphic units
  - Choose units to emphasize mappability, process, and time
- My mapping is not automated!
  - I have experimented, but without success
  - Major challenge is noisy data
  - Worth further exploration
- Interpret by eye: on-screen digitizing over the right backdrop image

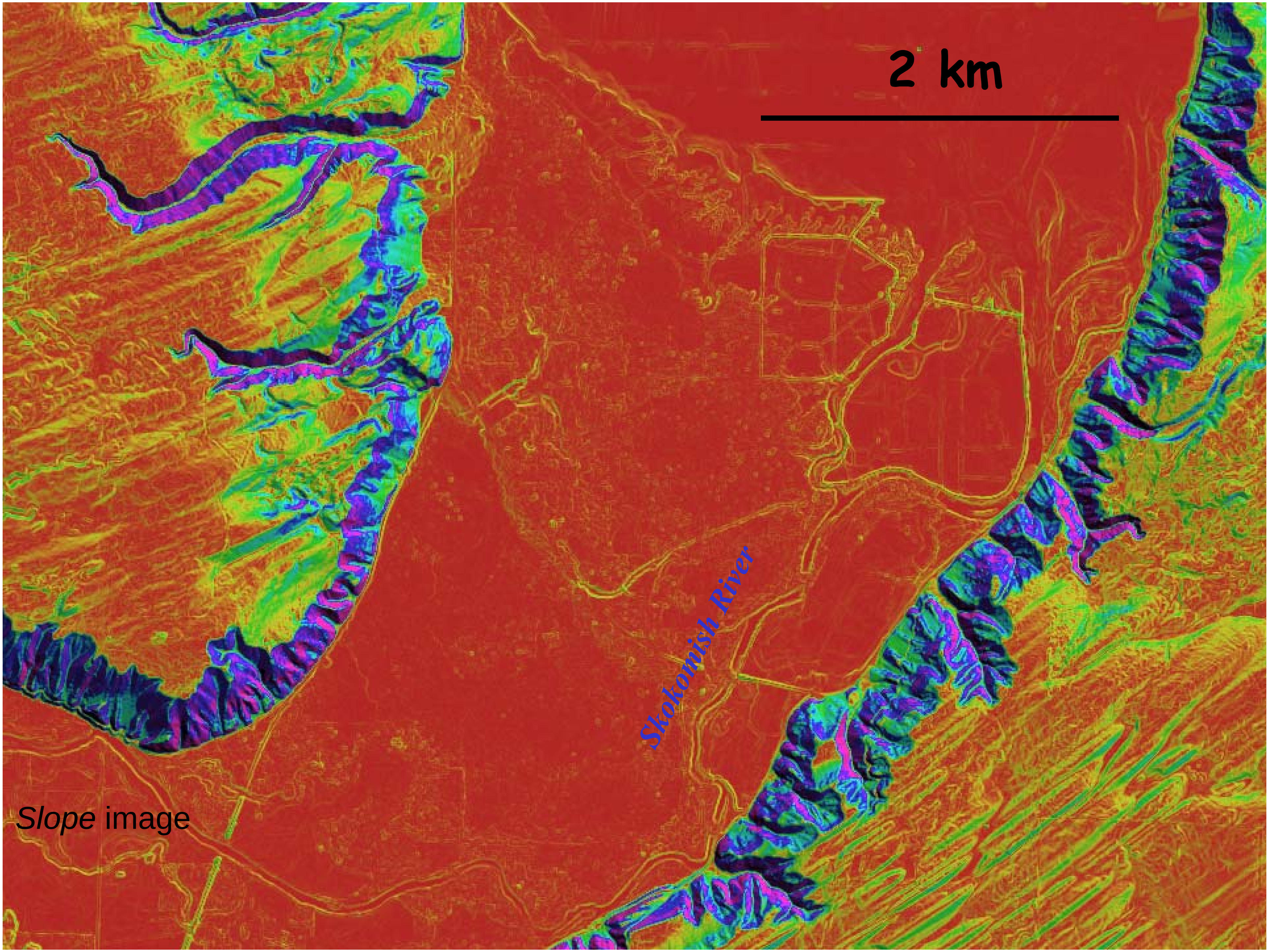
Map units defined inductively from observed phenomena

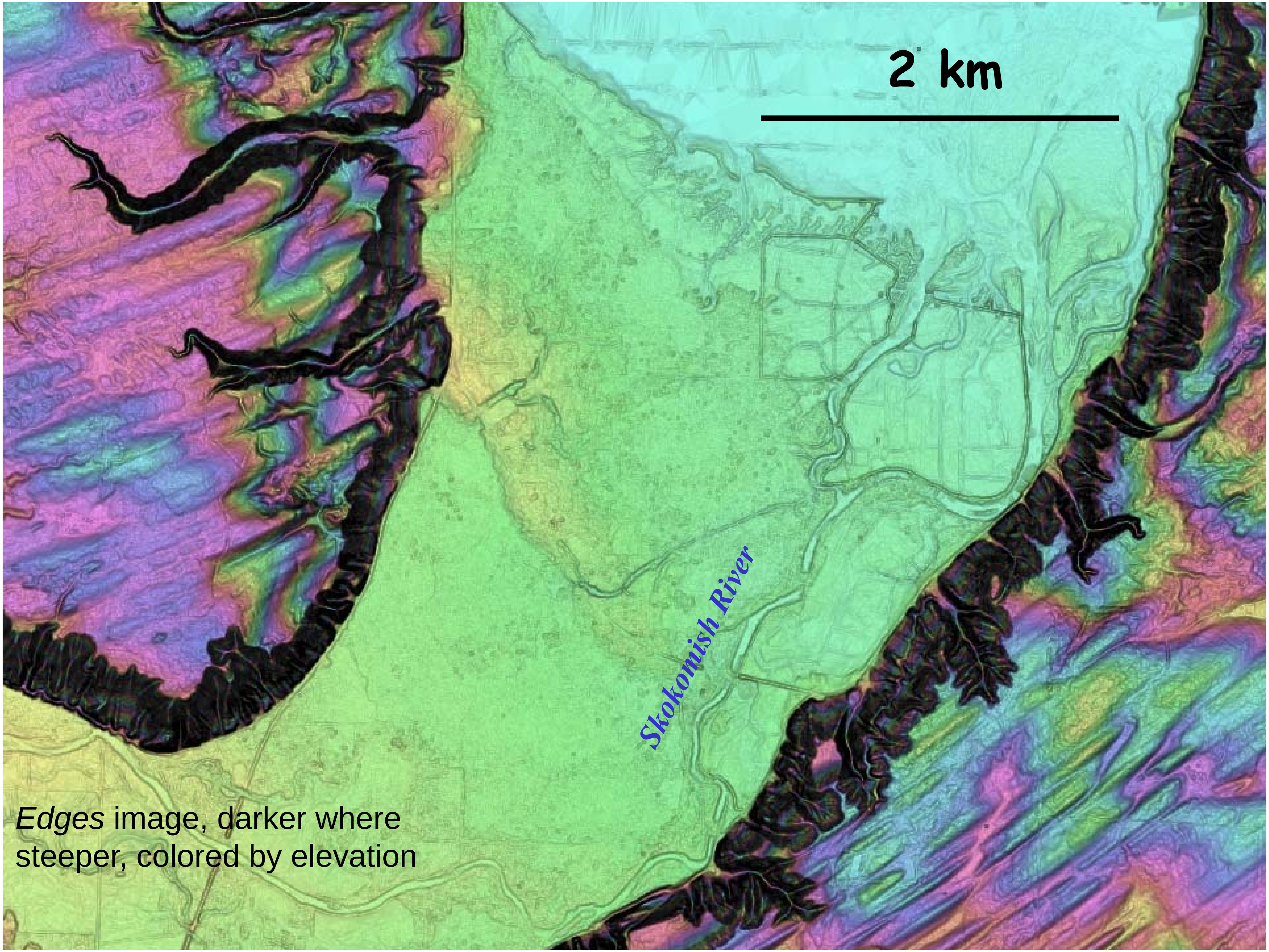
- Not deduced *a priori* from textbook principles. I wish to be open to unexpected classes of phenomena
- Map units defined on basis of texture, shape, and position
- Most contacts are at slope breaks
- Not all map units have an obvious genesis
- Mapping geomorphic units allows one to see (some) erosional history that is invisible to a focus on earth-material units

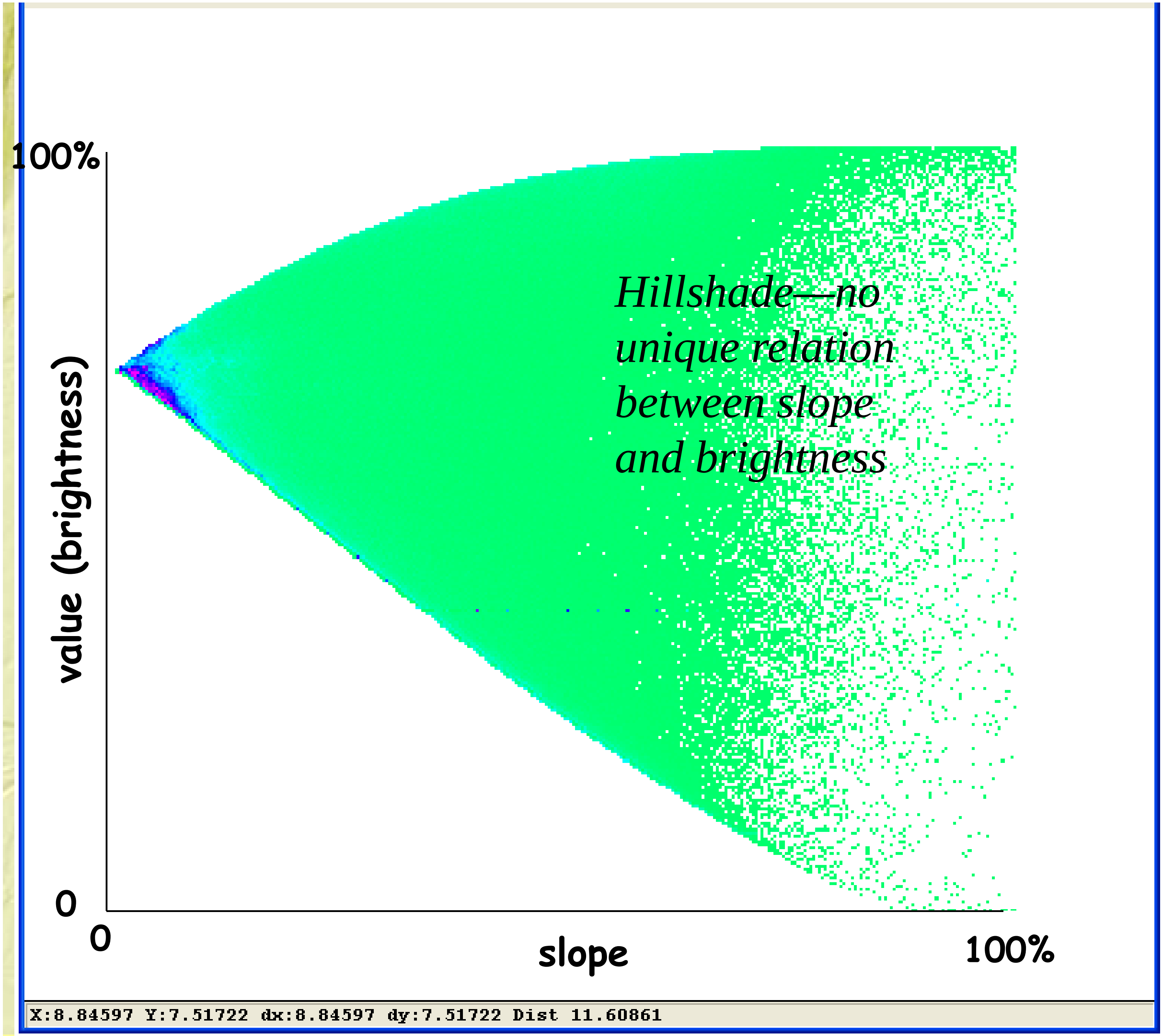

B
V
S
O
2 km
Calculate the right backdrop image
Skokomish River
Shaded-relief image of lidar topography, illumination from NW

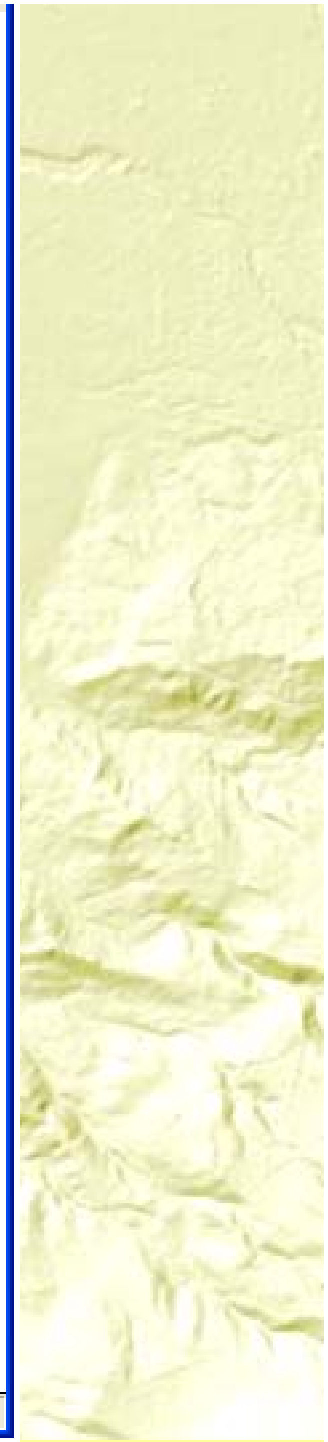


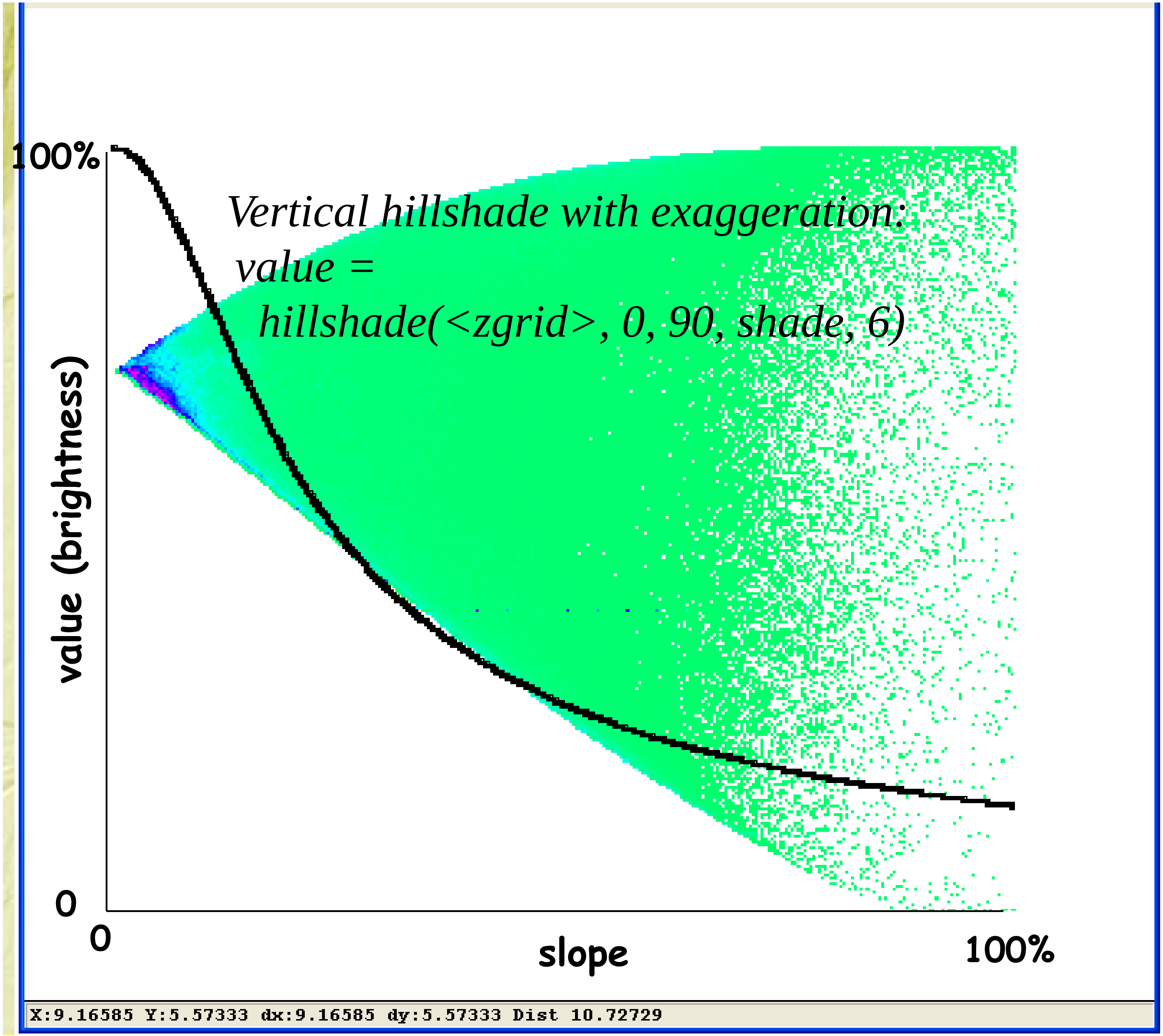
Shaded-relief image of lidar topography, illumination from NE

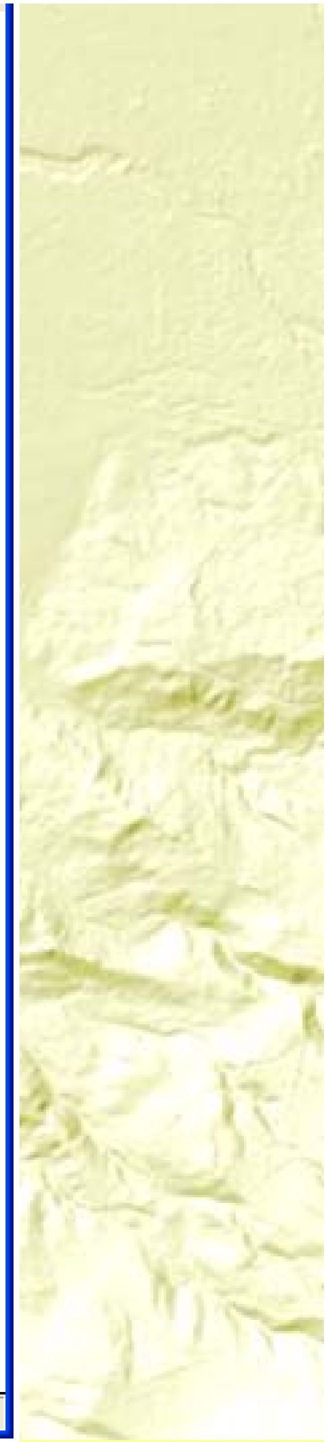

2 km
Skokomish River
Slope image

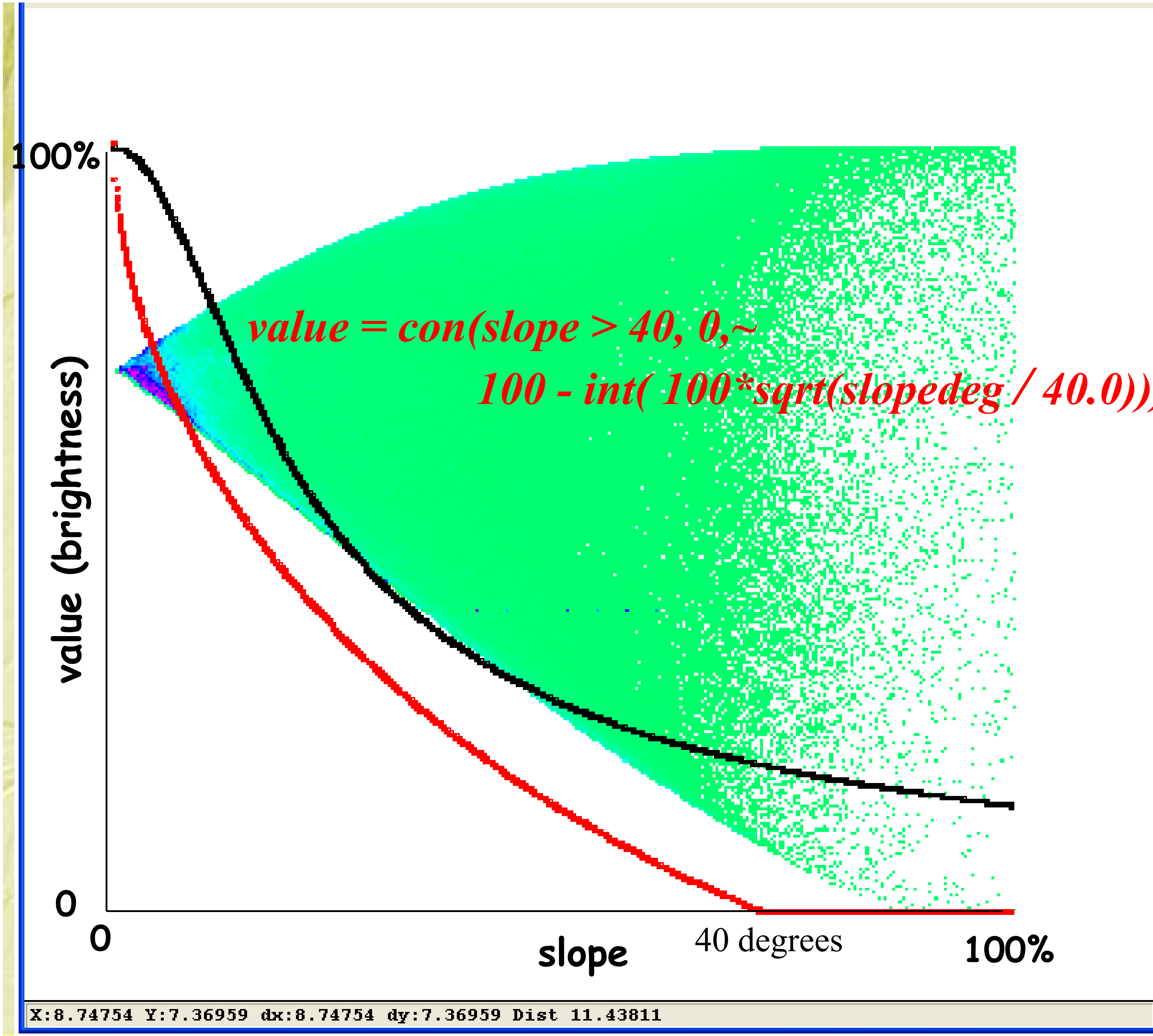

2 km
Skokomish River
Edges image, darker where steeper, colored by elevation

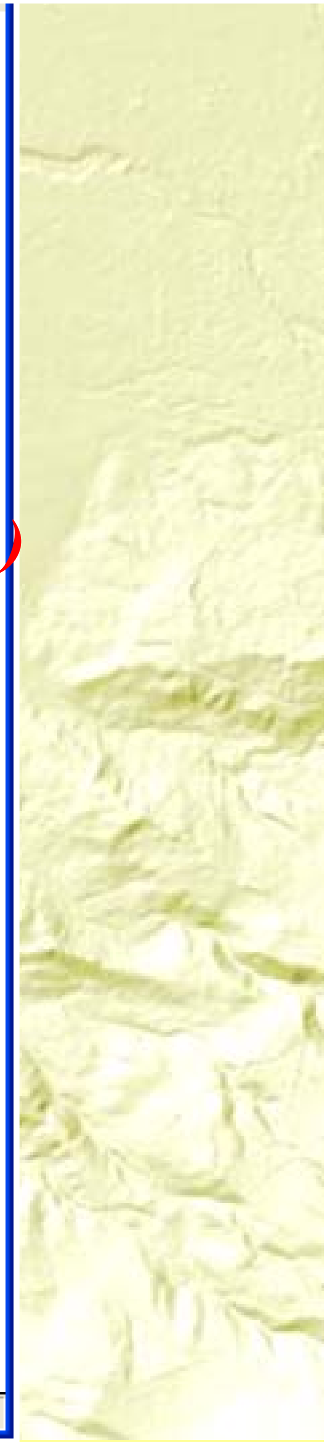

100%
value (brightness)
0
0
slope
100%
Hillshade—no unique relation between slope and brightness
X:8.84597 Y:7.51722 dx:8.84597 dy:7.51722 Dist 11.60861

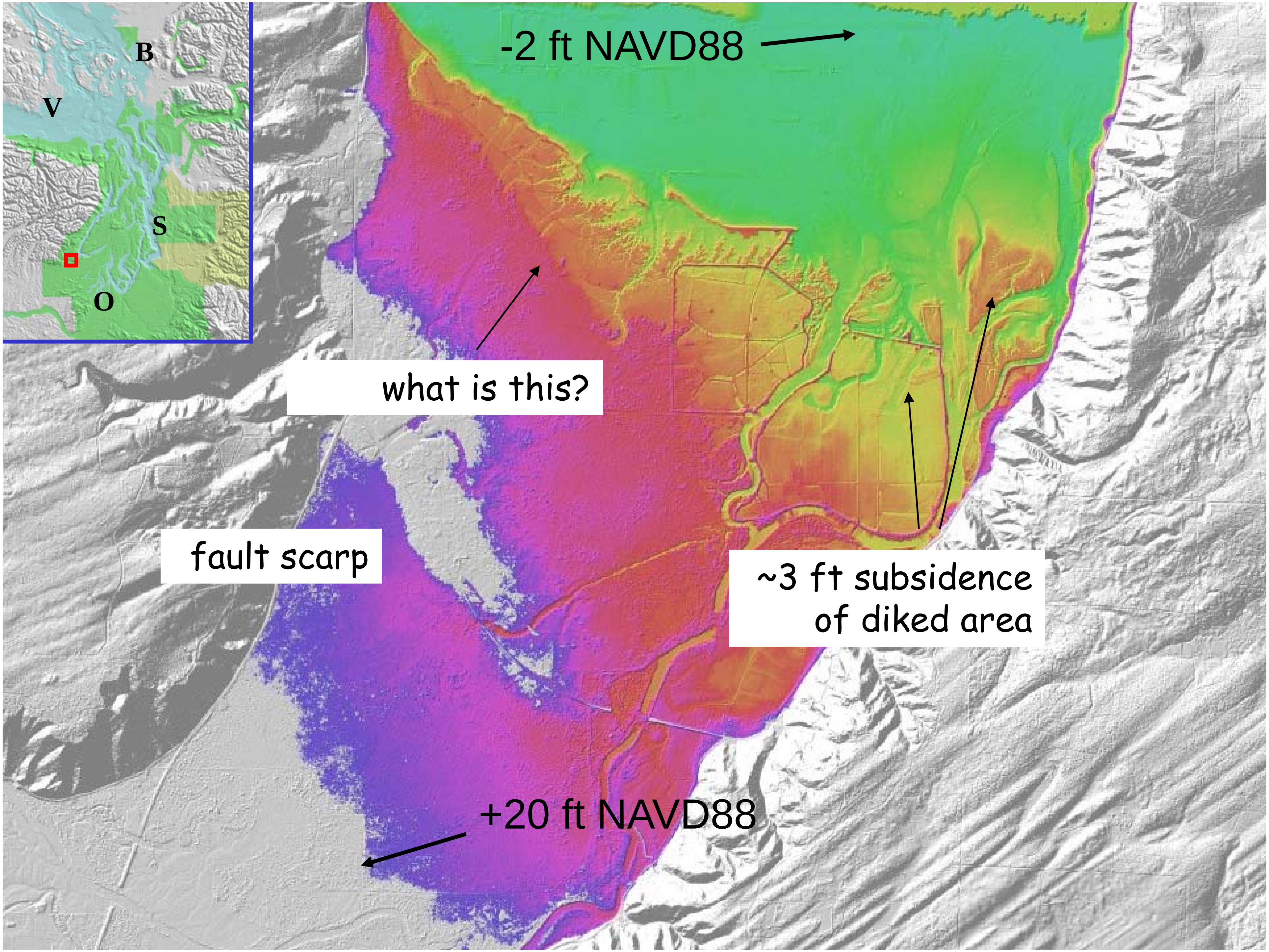



Vertical hillshade with exaggeration:
value =
hillshade(<zgrid>, 0, 90, shade, 6)
100%
value (brightness)
0
0
slope
100%
X:9.16585 Y:5.57333 dx:9.16585 dy:5.57333 Dist 10.72729




100%
value (brightness)
0
value = con(slope > 40, 0,~
100 - int(100*sqrt(slopedeg / 40.0)))
0
slope
40 degrees
100%
X:8.74754 Y:7.36959 dx:8.74754 dy:7.36959 Dist 11.43811





B
V
S
O
-2 ft NAVD88
what is this?
fault scarp
~3 ft subsidence of diked area
+20 ft NAVD88

Challenges

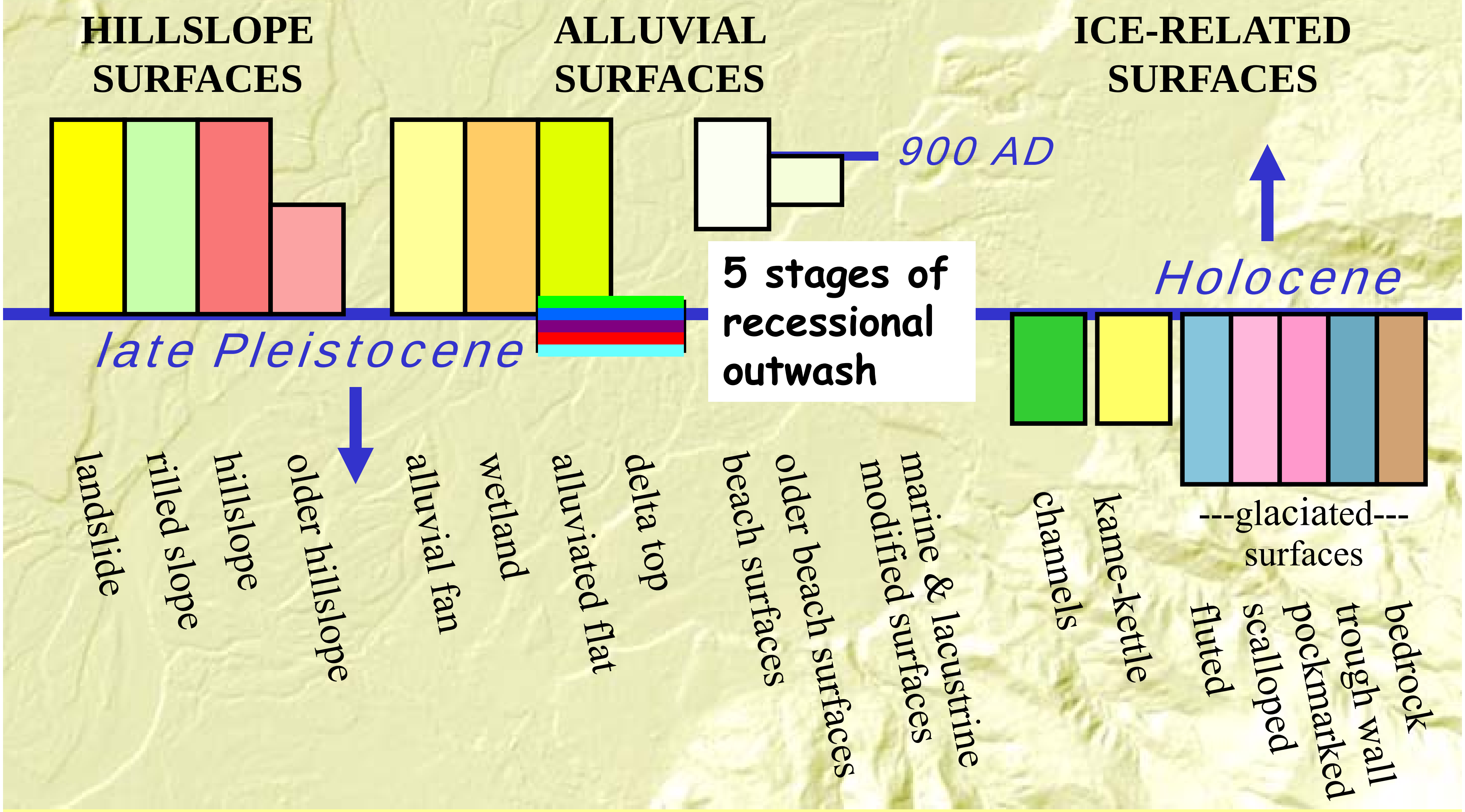
- Human modification of the landscape
  - Where to map modified land? One needs to make a policy decision
- Artifacts in the DEM
  - I try to map what I interpret the ground to truly be
- What scale am I mapping at?
  - Working scale typically ~6 x nominal scale
- Are my map units adequate?

Mostly not a challenge:

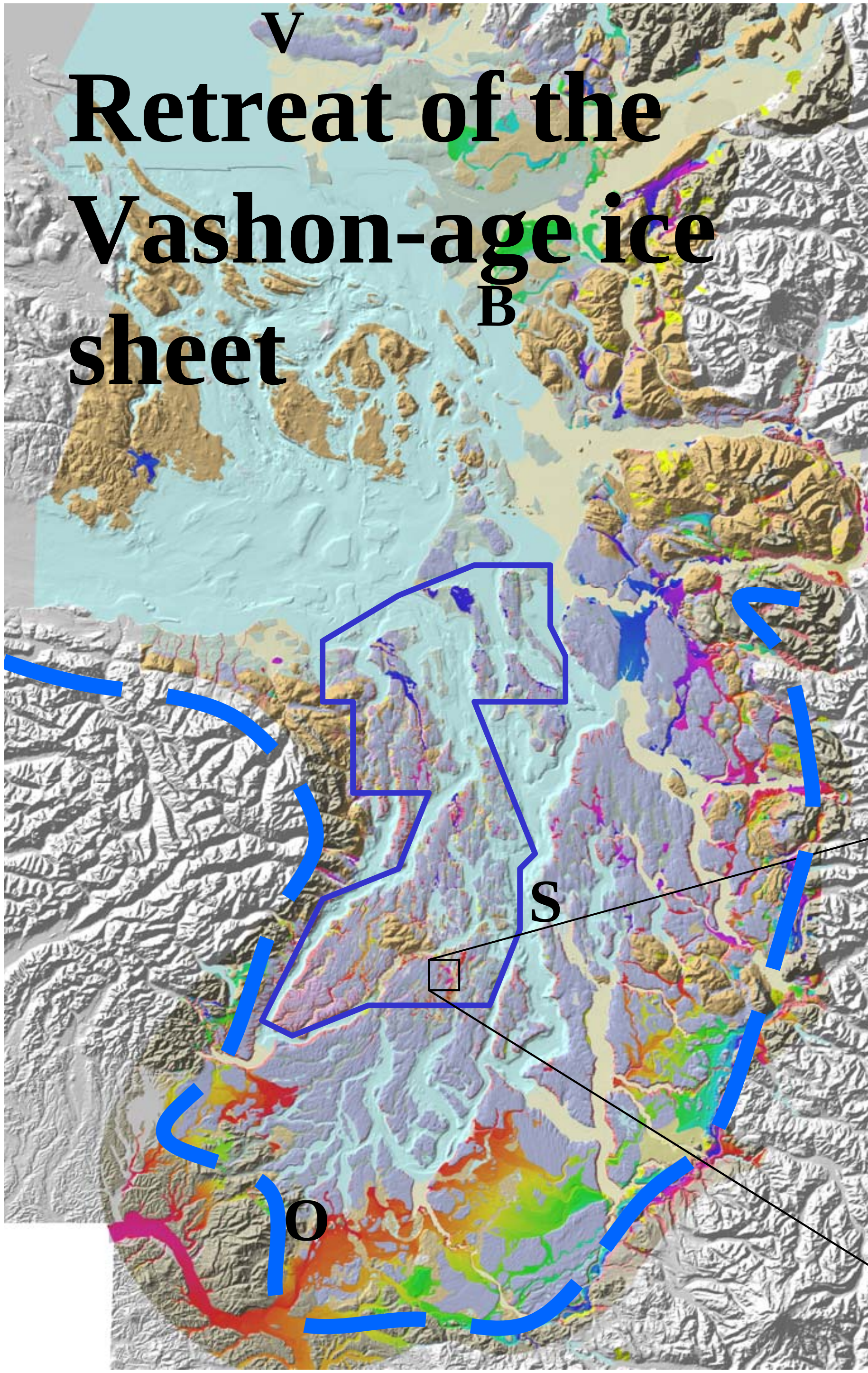
- Overprinting (e.g., dunes on top of alluvial flats, diffusional modification of hillslope edges)

5. Earth history

Surface "stratigraphy" of the Puget Lowland

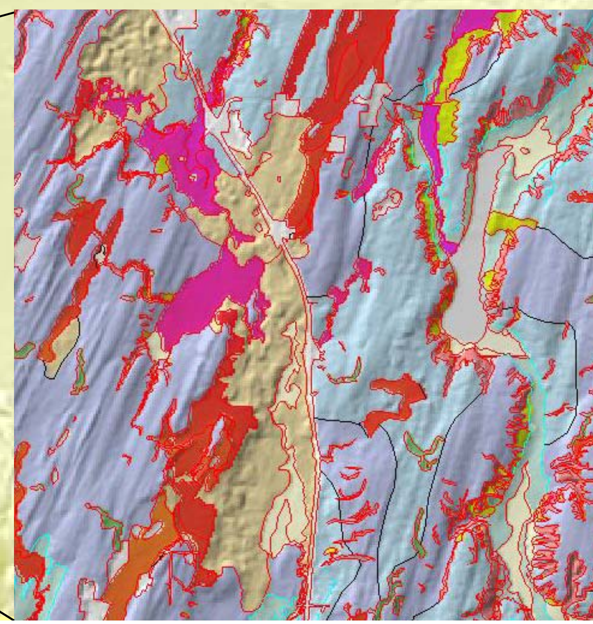


Retreat of the Vashon-age ice sheet

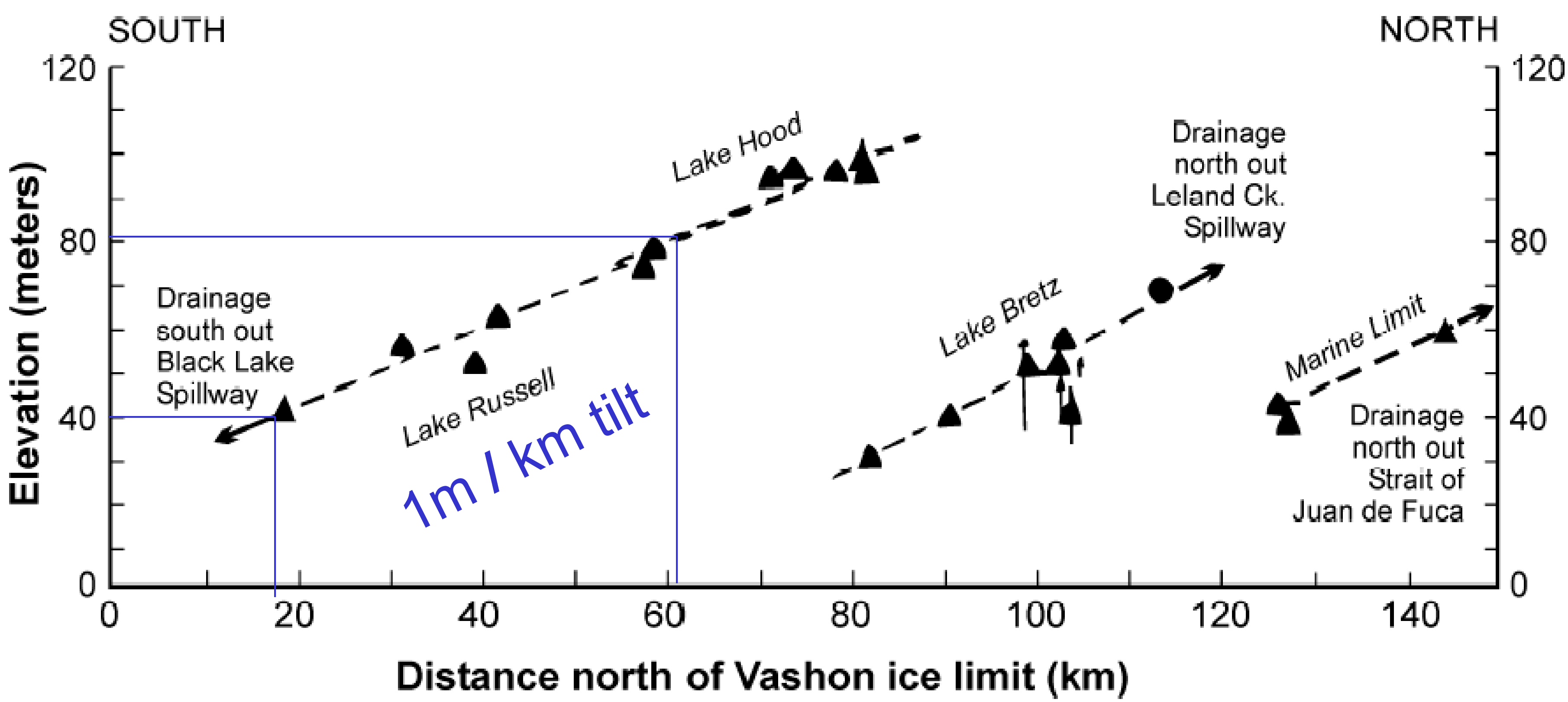


Analysis based on:

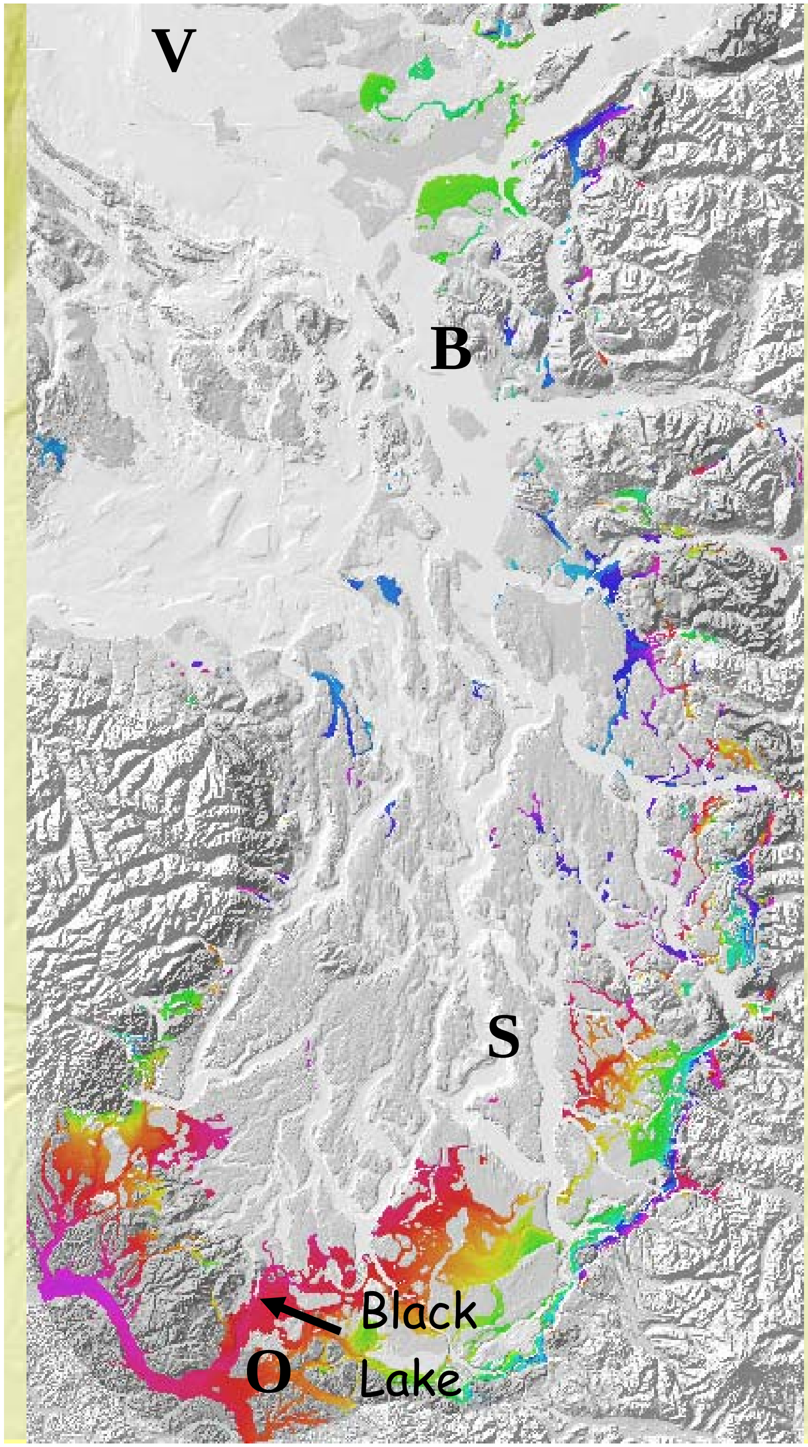
- Geomorphic mapping of region from 30m/25m DEMs
- Geomorphic mapping of central area from 6ft lidar DEMs
- Local revision with David Finlayson's 30ft composite DEM (http://www.ocean.washington.edu/data/pugetsound)



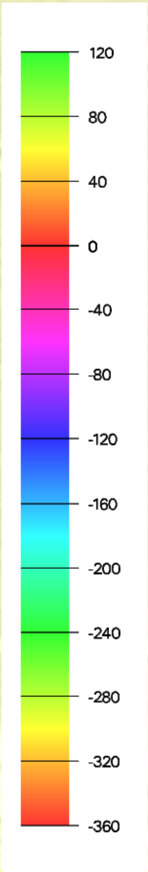
Glacio-isostatic rebound documented from displaced deltas by Thorson (1989) and Dethier and others (1995)



from Booth and others, 2004

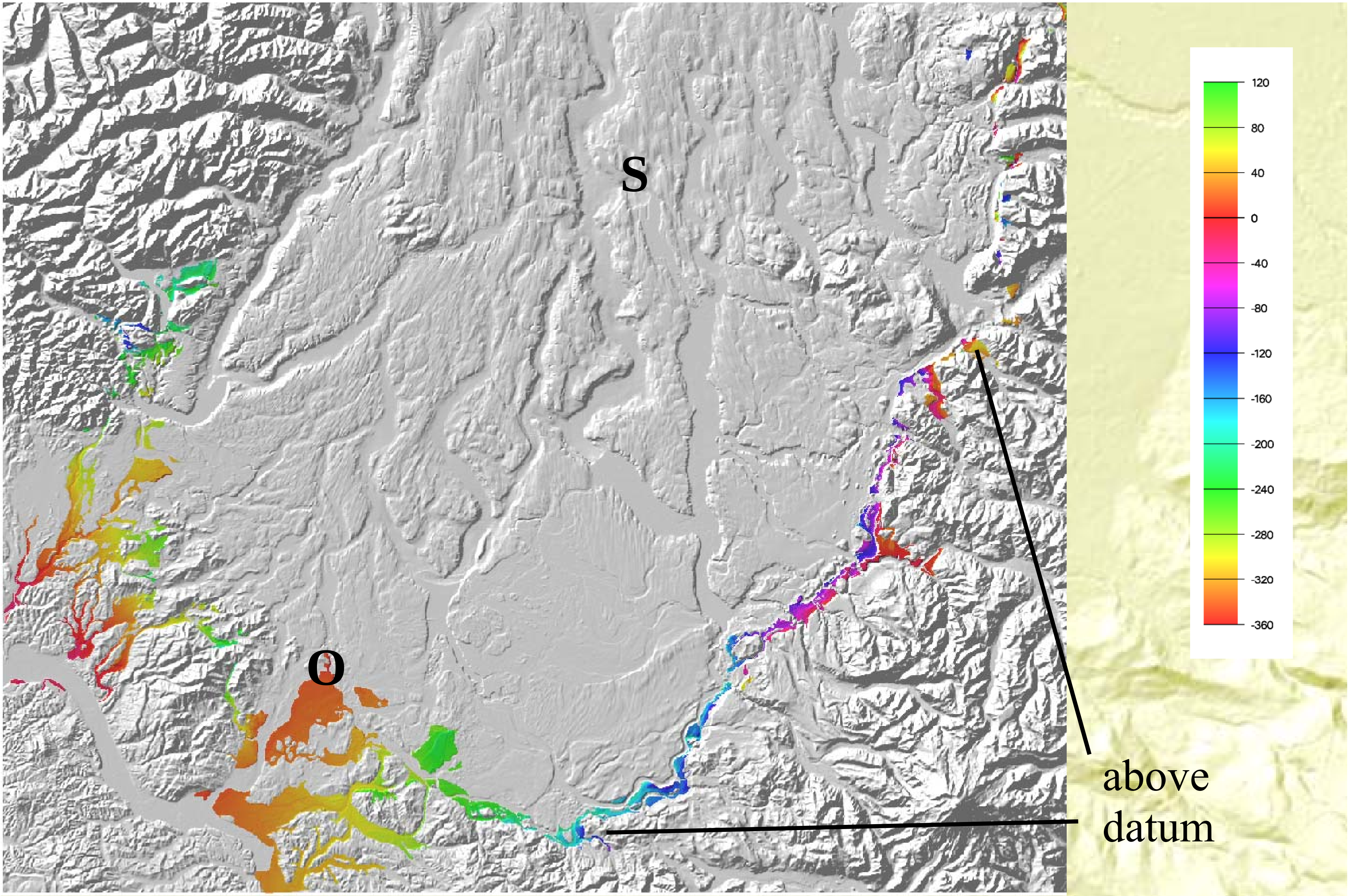


Late Vashon age alluvial flats (outwash streams, delta tops, beaches)

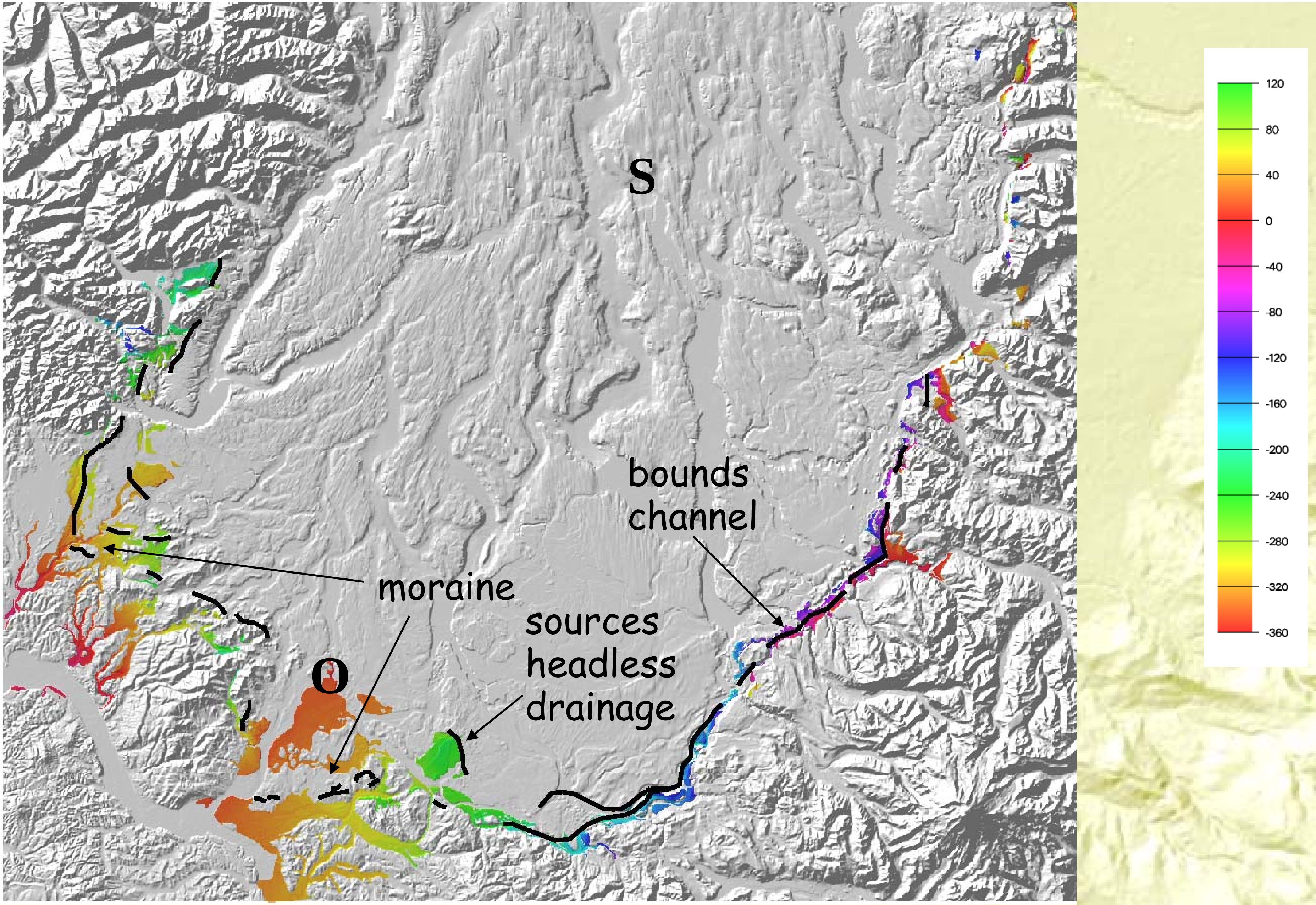


Colored by elevation relative to late Pleistocene Black Lake datum

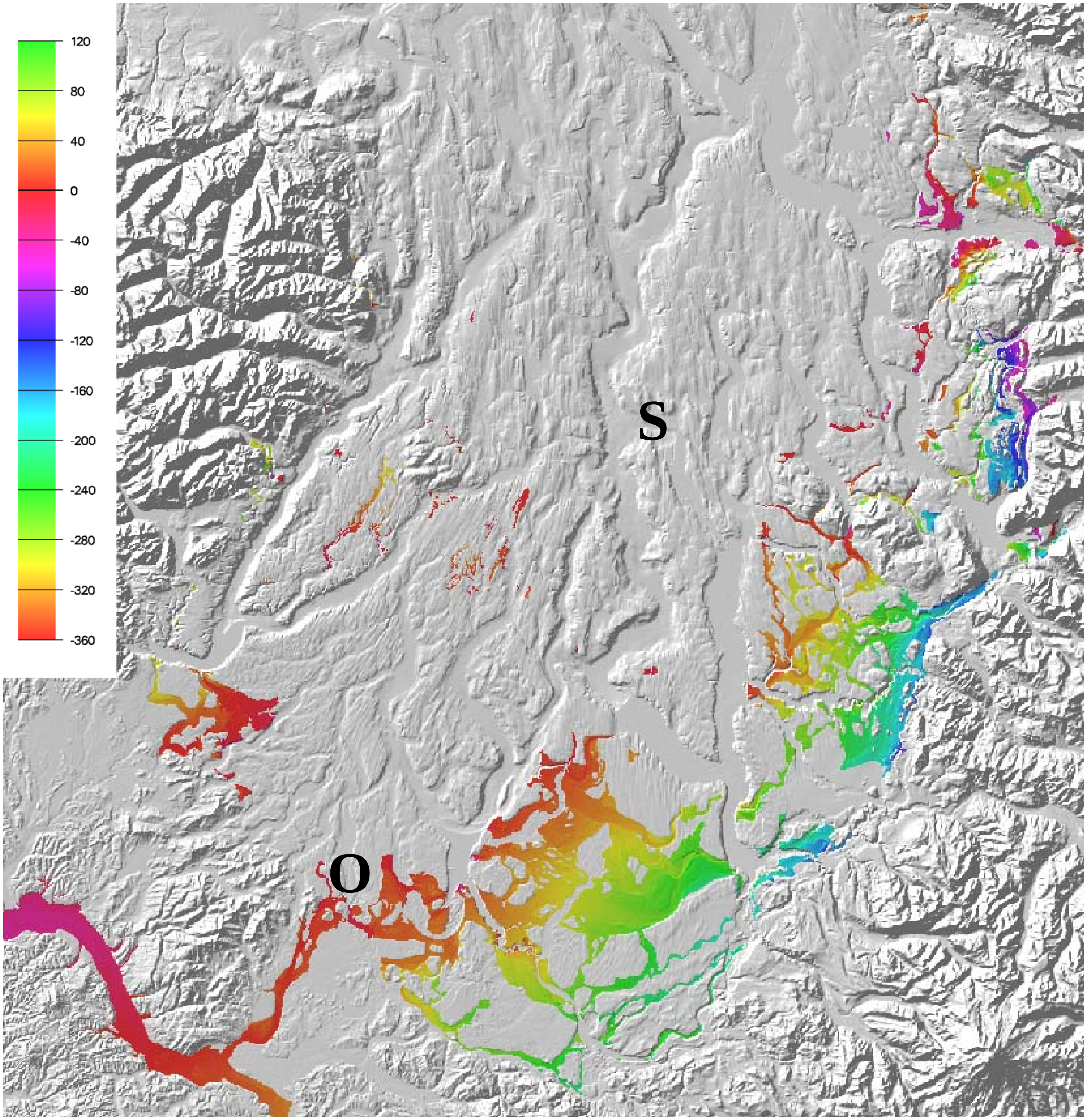
(1 m/km down-to-north tilt)



Outwash surfaces formed at maximum ice-sheet extent

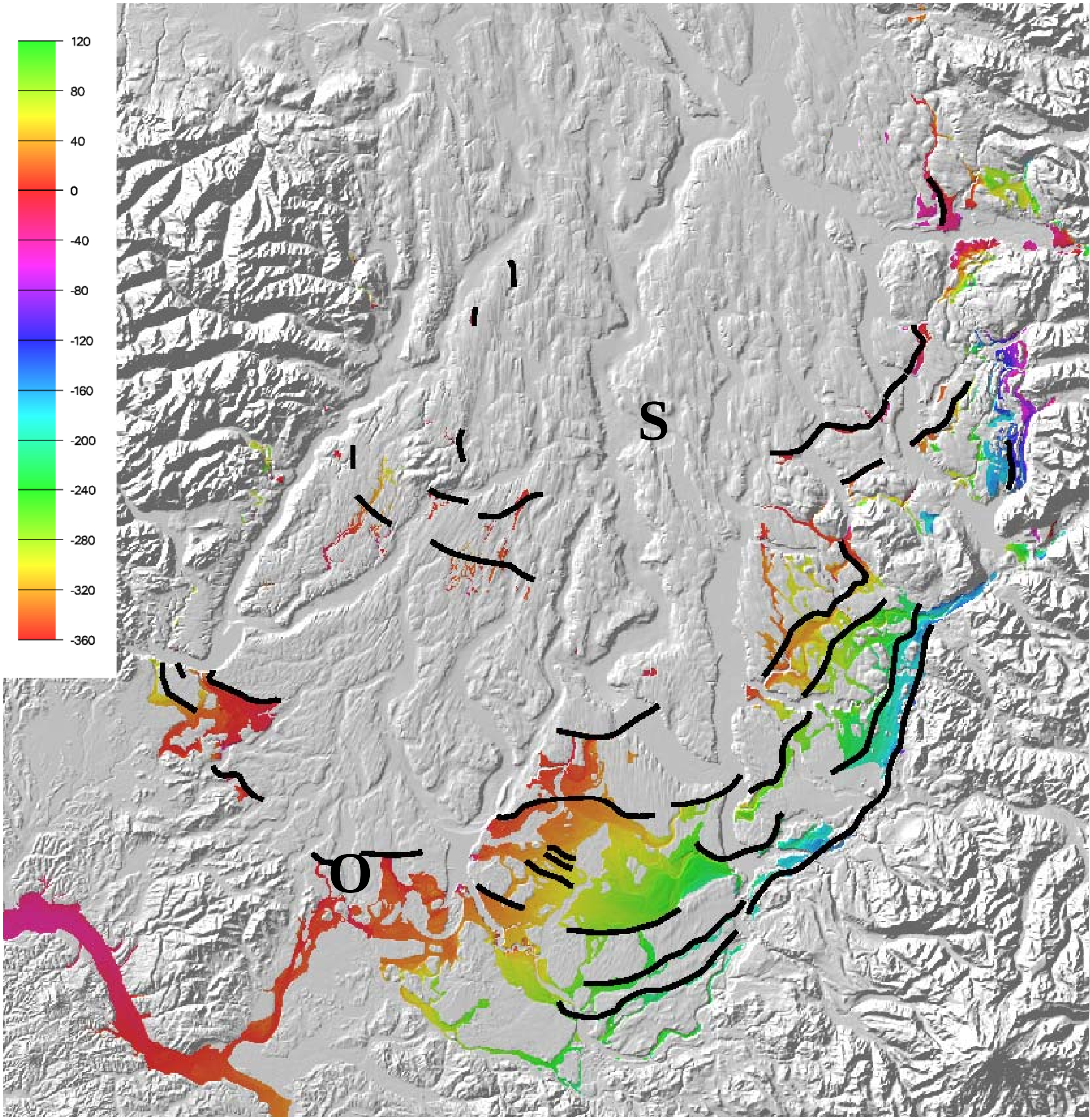


Outwash surfaces formed at maximum ice-sheet extent



Outwash surfaces formed at time of Lake Russell *(lake drains to south)*

Lake levels 0 to 60 m below datum



Outwash surfaces formed at time of Lake Russell *(lake drains to south)*

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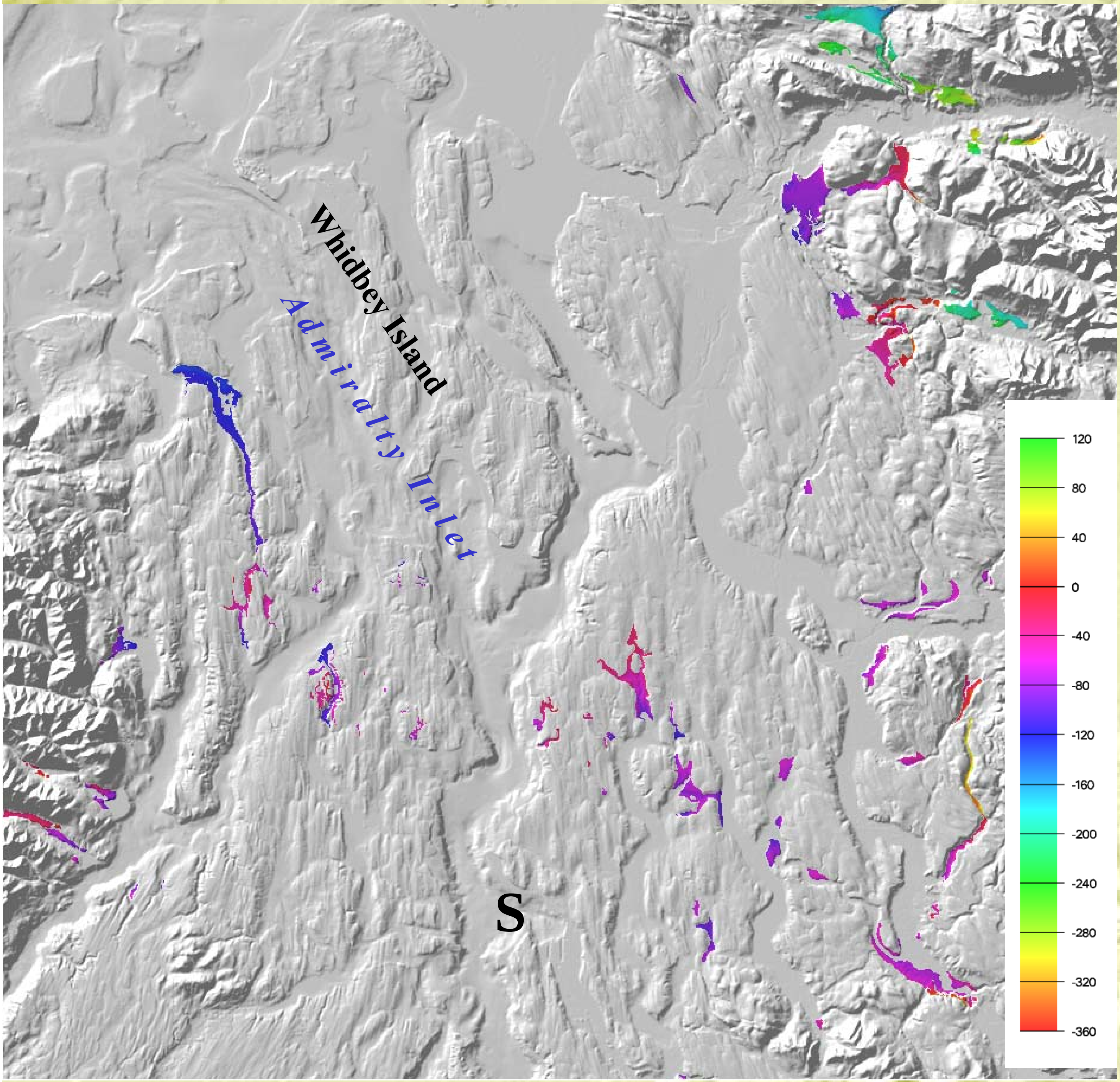
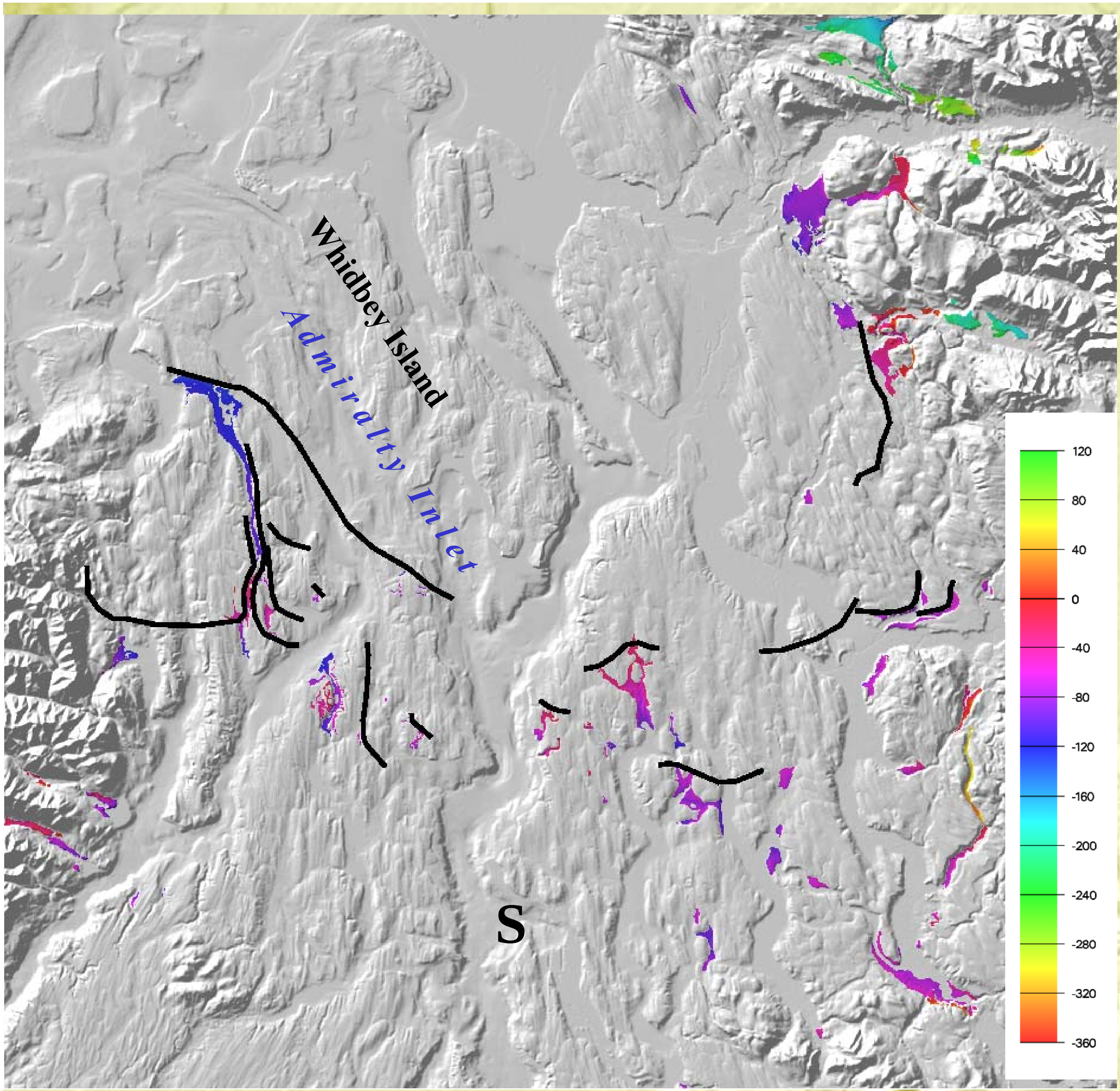


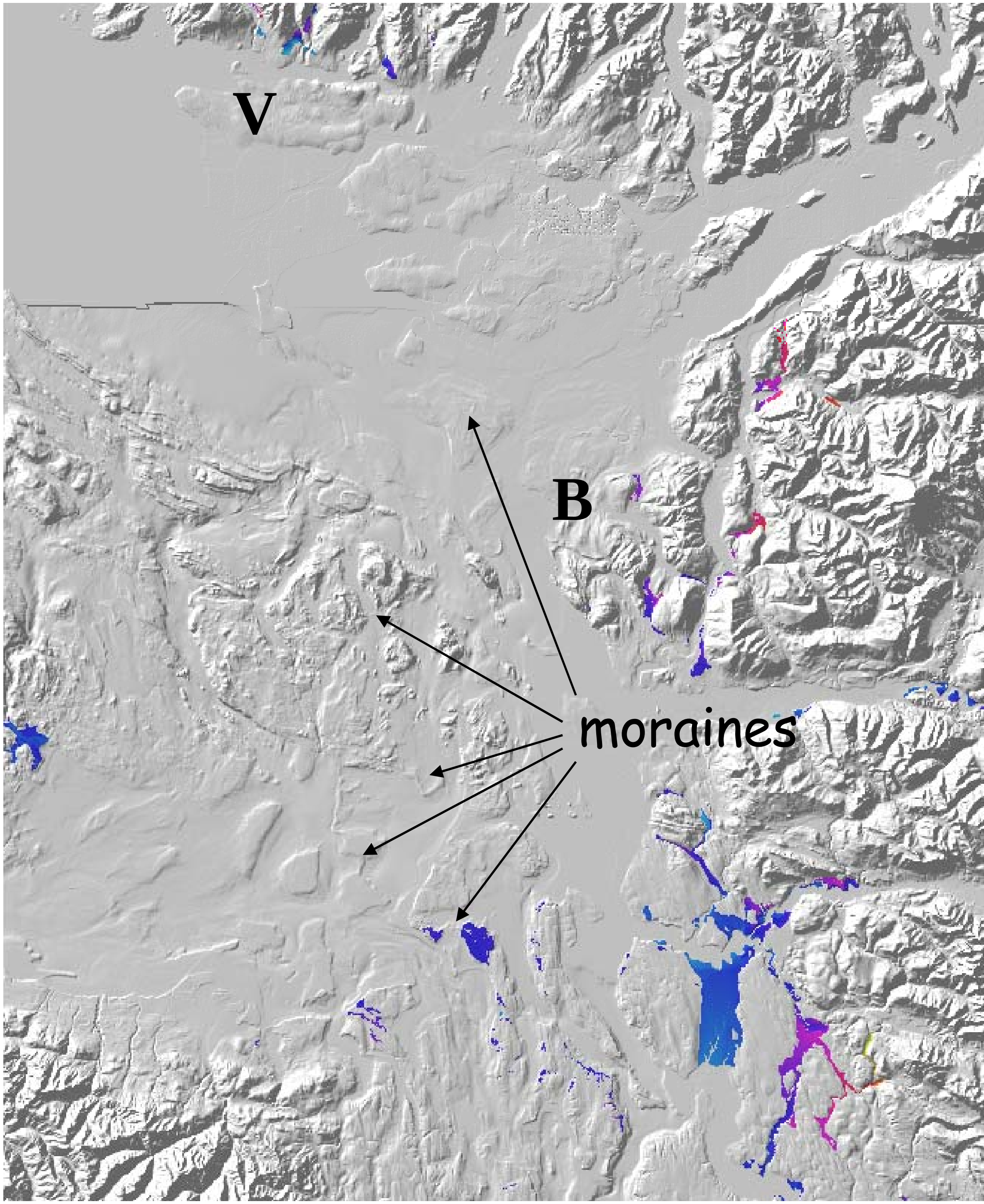
Outwash surfaces formed at time of Lake Bretz *(lake drains to north)*

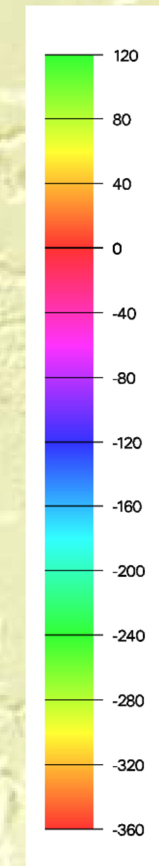
Lake levels 90 to 140 m below datum



Outwash surfaces formed at time of Lake Bretz *(lake drains to north)*

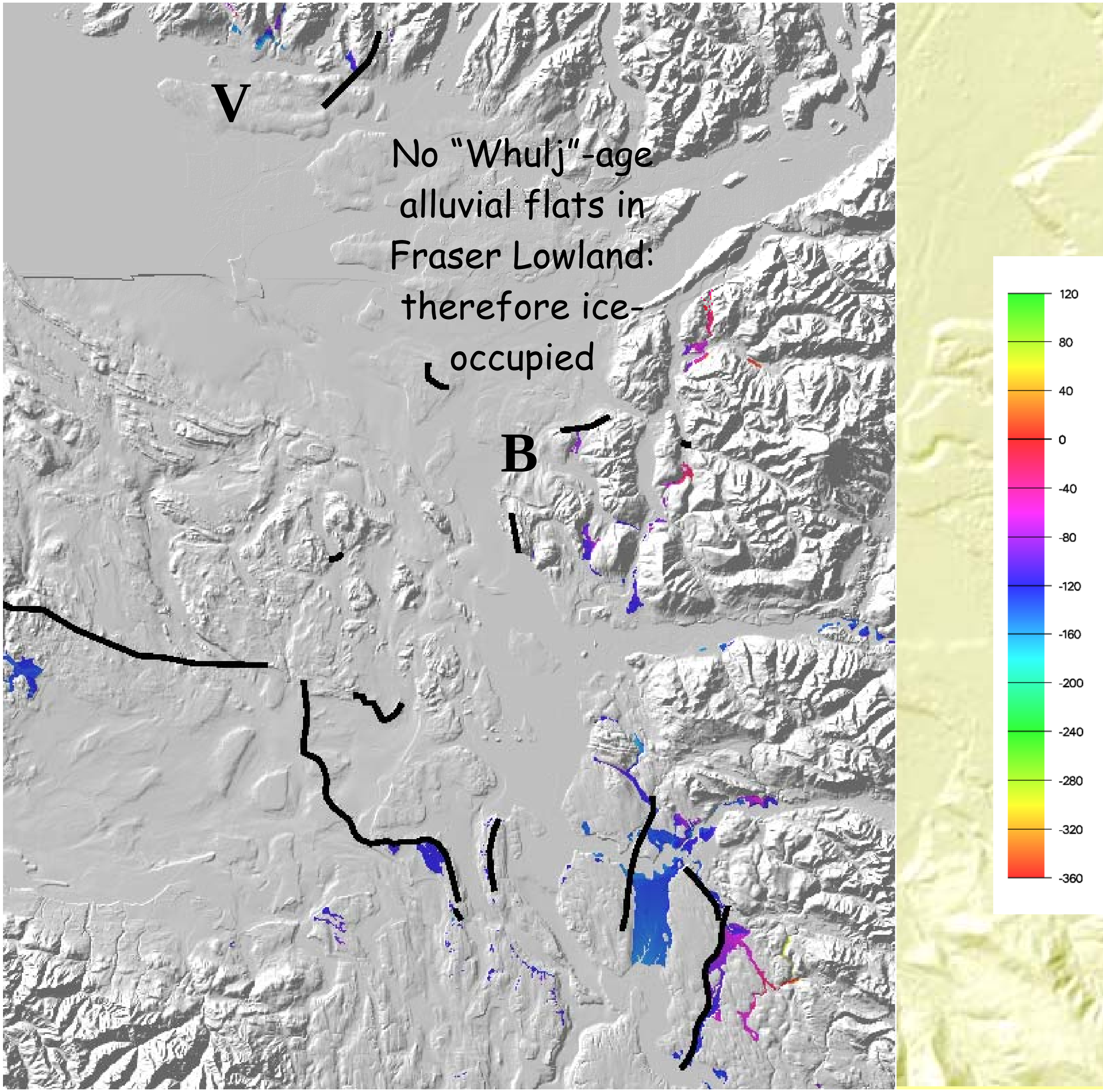
Lake levels 90 to 140 m below datum





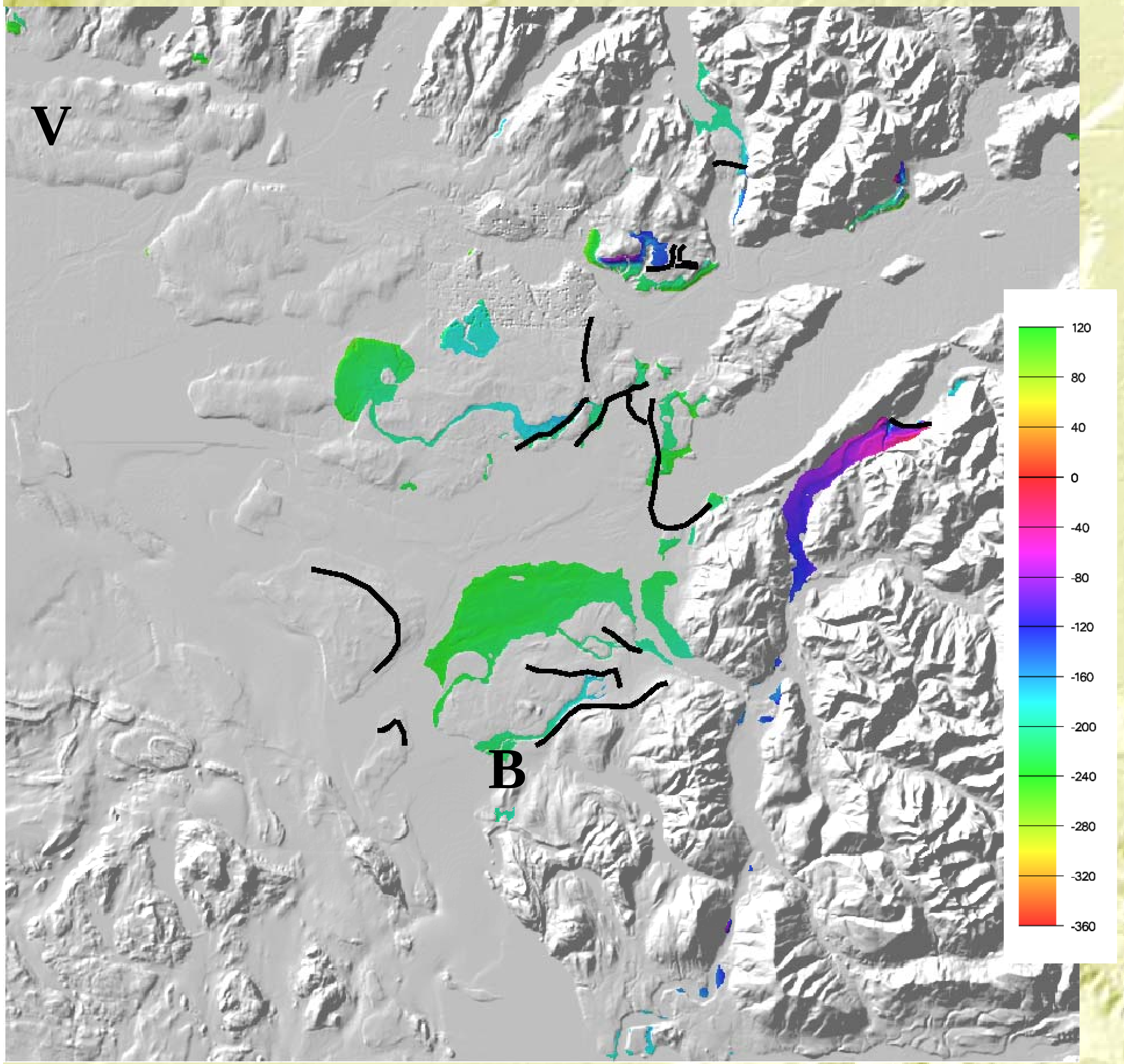
Outwash surfaces formed at "Whulj" time *(lakes gone, marine deposition)*

Sea level ~140 m below datum



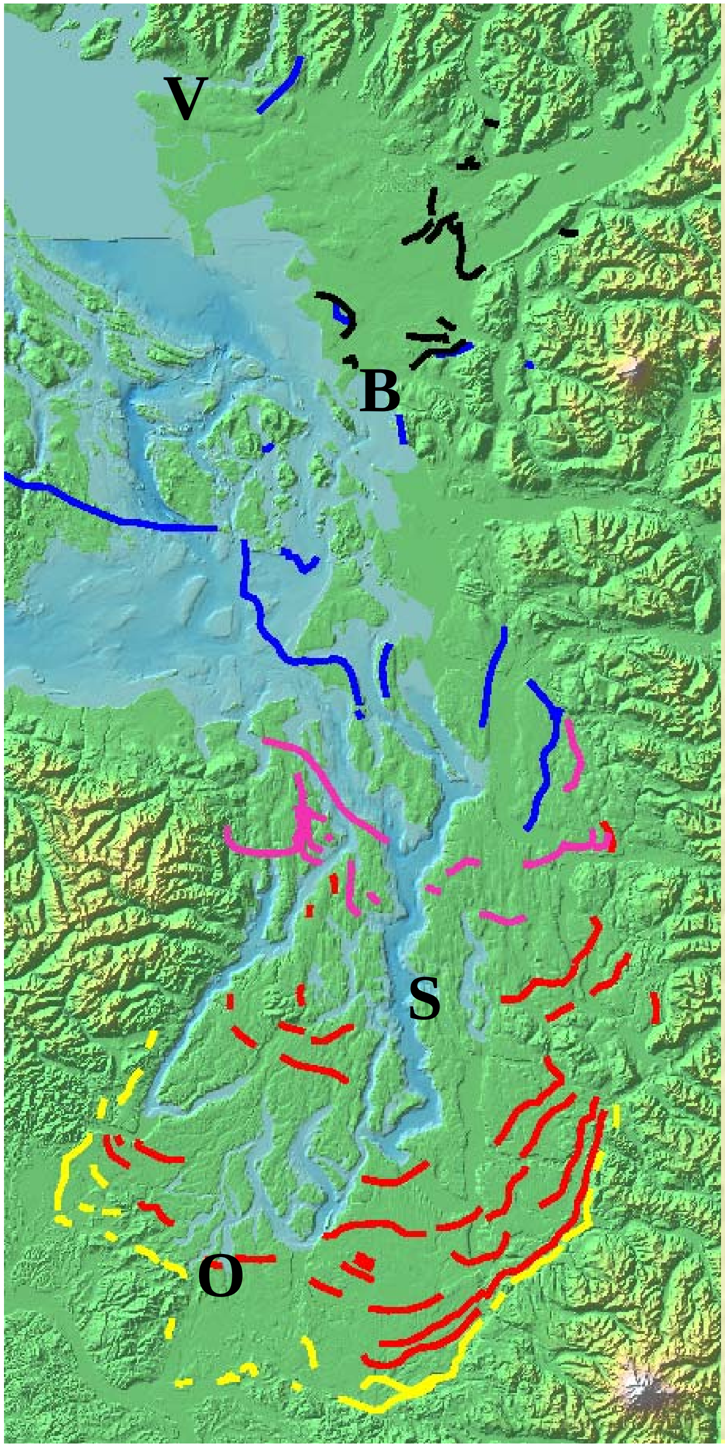
Outwash surfaces formed at "Whulj" time *(lakes gone, marine deposition)*

Sea level ~140 m below datum



Outwash surfaces formed in Sumas time

Sea level 220 to 260 m below datum

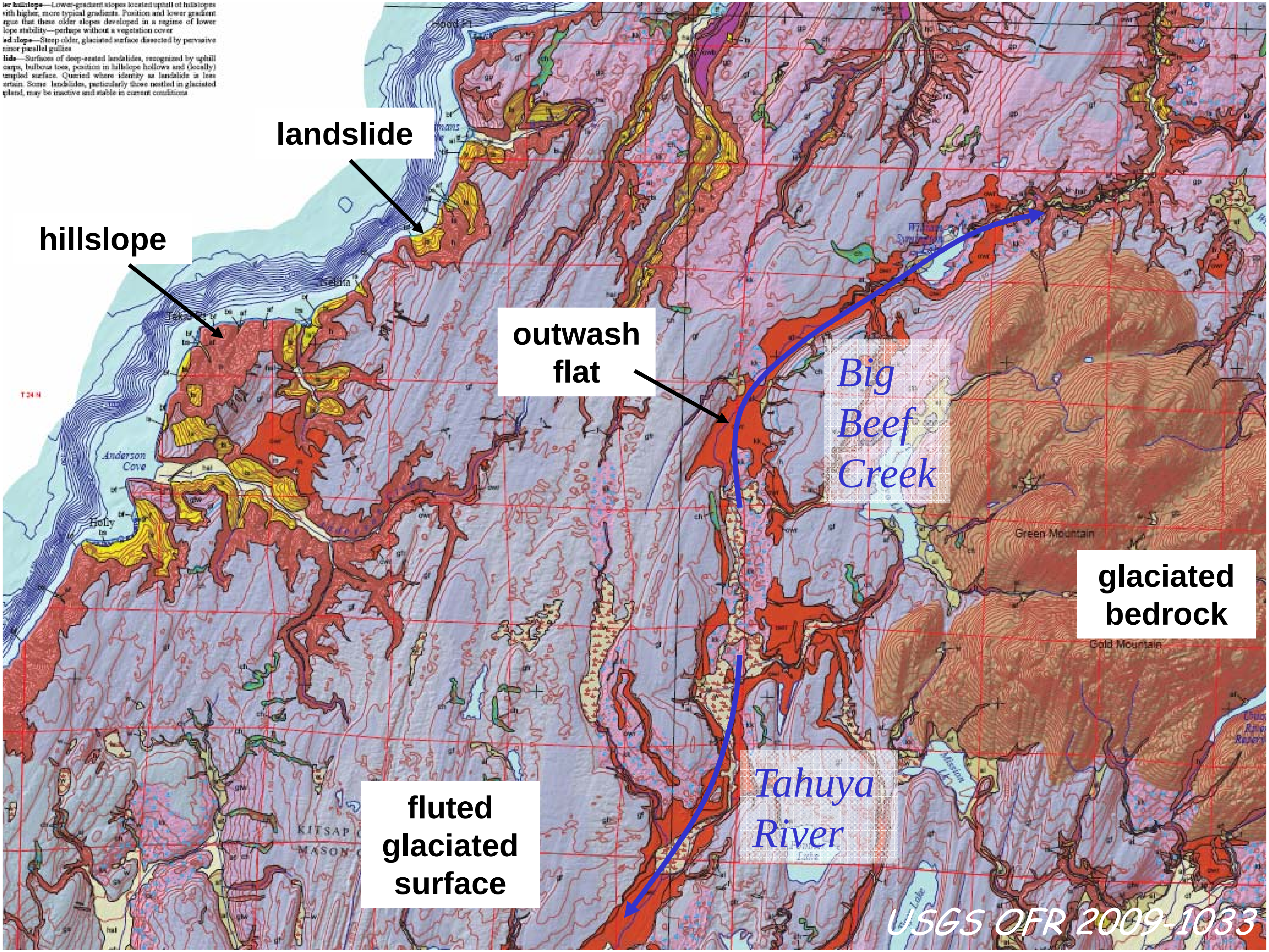


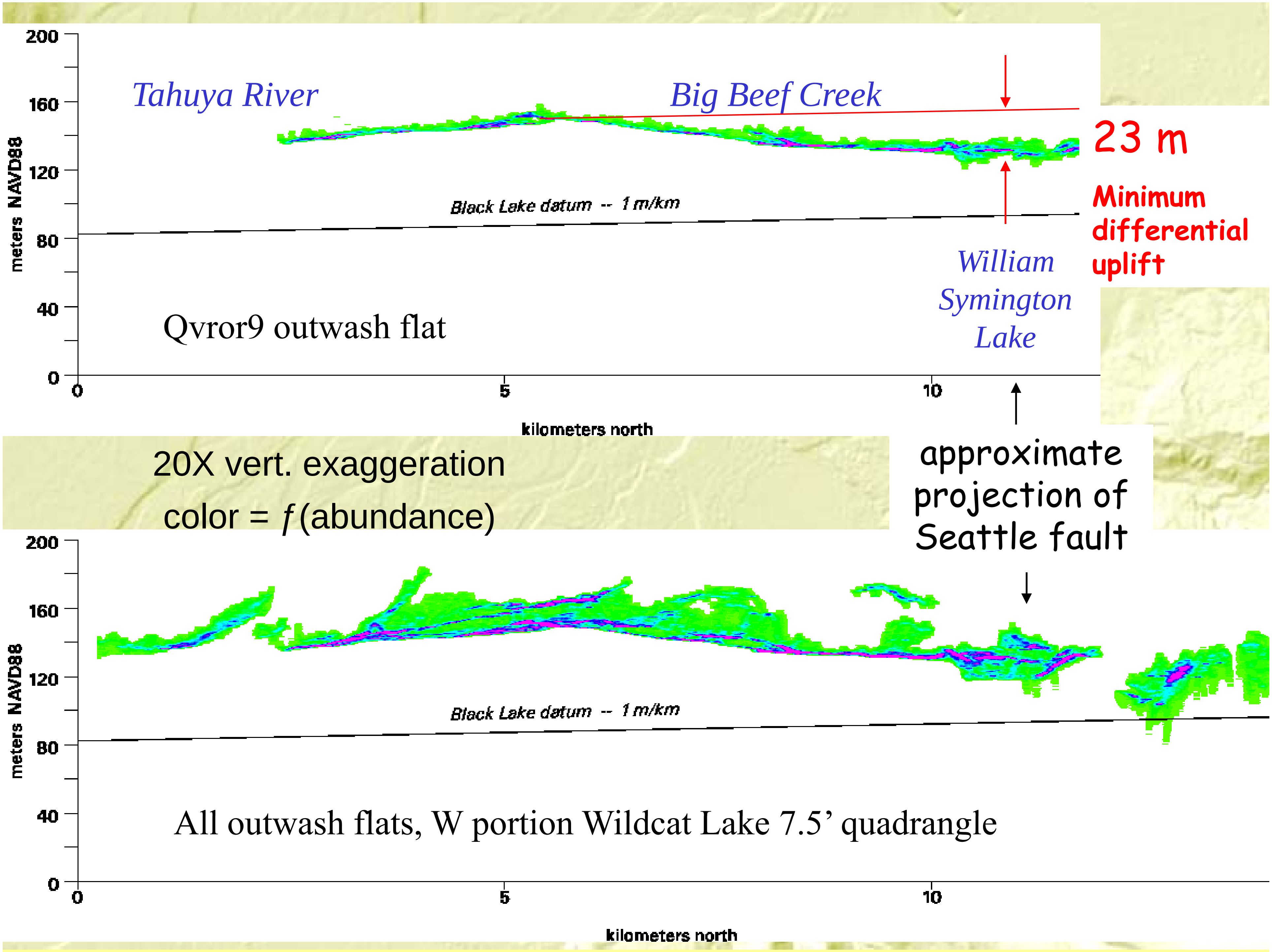
A history of progressive deglaciation is preserved in topography

Ice margins

Sumas
Whulge
Bretz
Russell
Main

View E along Seattle fault, SE Bainbridge Island


landslide
hillslope
outwash flat
Big Beef Creek
glaciated bedrock
fluted glaciated surface
Tahuya River
USGS OFR 2009-1033

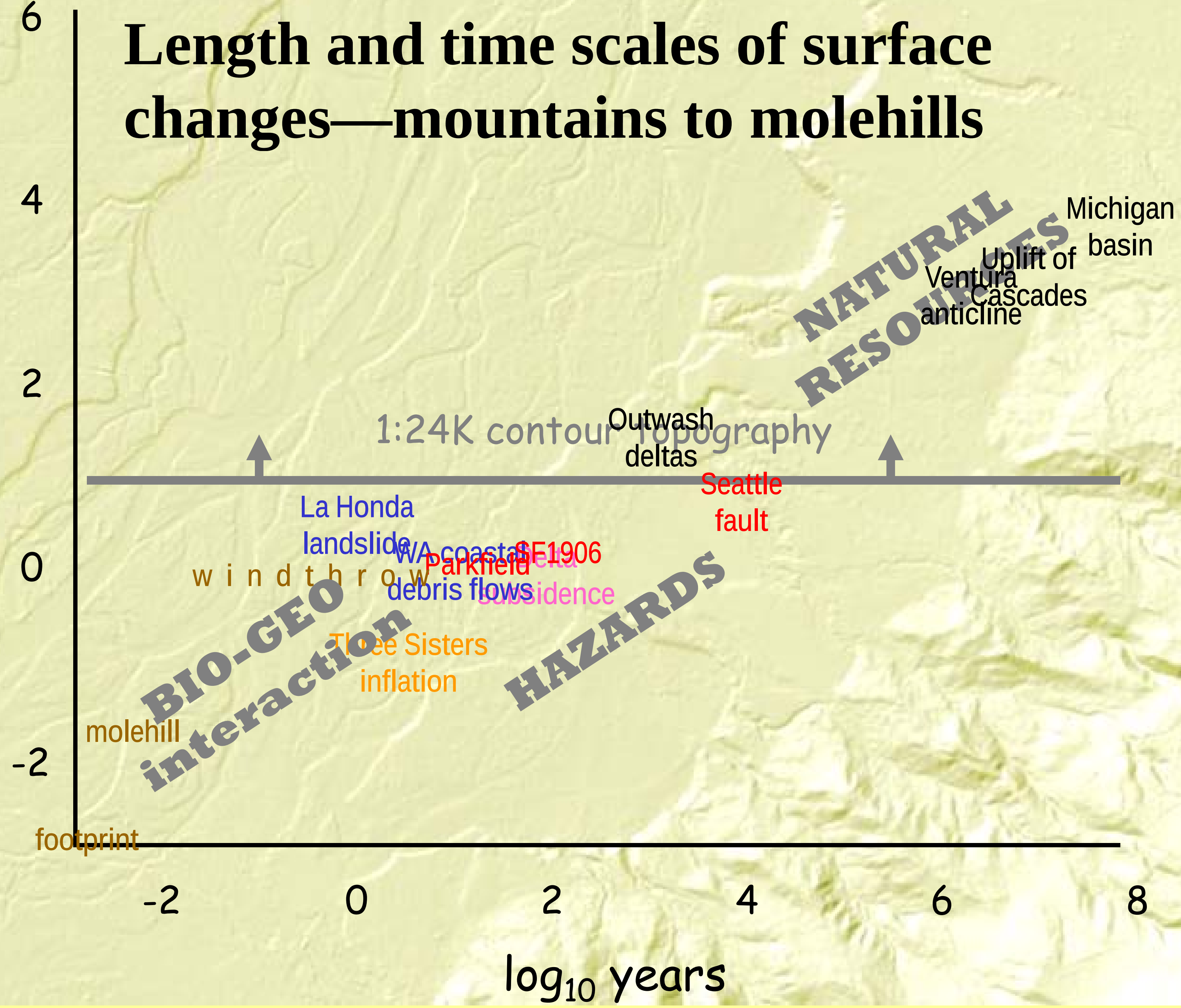


200
160
120
80
40
0
meters NAVD88
Tahuya River
Big Beef Creek
23 m
Minimum differential uplift
Black Lake datum -- 1 m/km
William Symington Lake
Qvror9 outwash flat
0
5
10
kilometers north
20X vert. exaggeration
color = *f* (abundance)
approximate projection of Seattle fault
200
160
120
80
40
0
meters NAVD88
Black Lake datum -- 1 m/km
All outwash flats, W portion Wildcat Lake 7.5' quadrangle
0
5
10
kilometers north

Reflections on geomorphic mapping

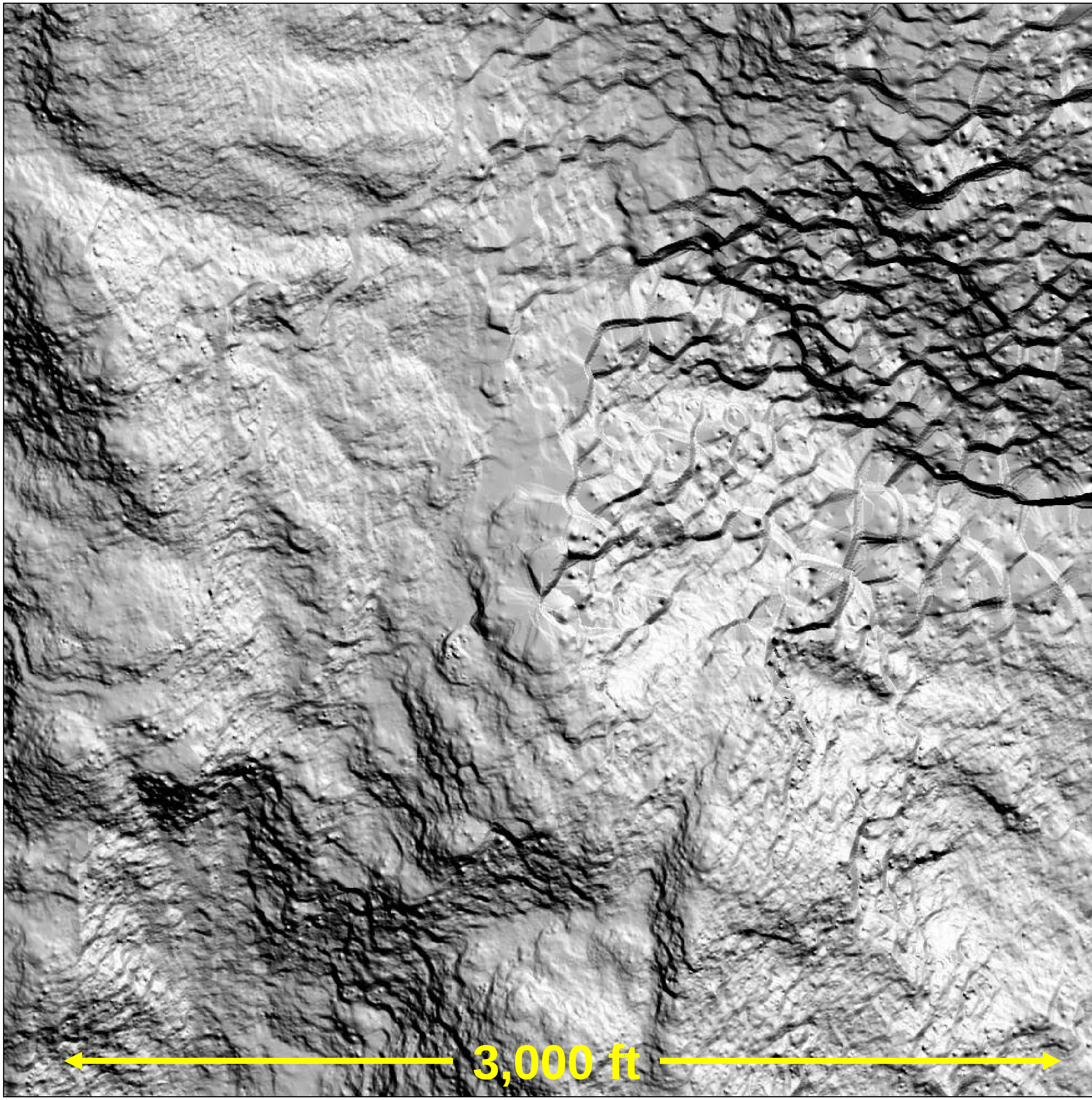
- Topographic data are commonly richer than geologic data
- Geomorphic maps inventory erosional as well as aggradational features, thus complement and extend the rock-and-deposit record
- At least in the Puget Lowland, landscape development was punctuated
- Improved spatial resolution (lidar) translates into improved resolution of landscape process and improved temporal resolution

Length and time scales of surface changes—mountains to molehills



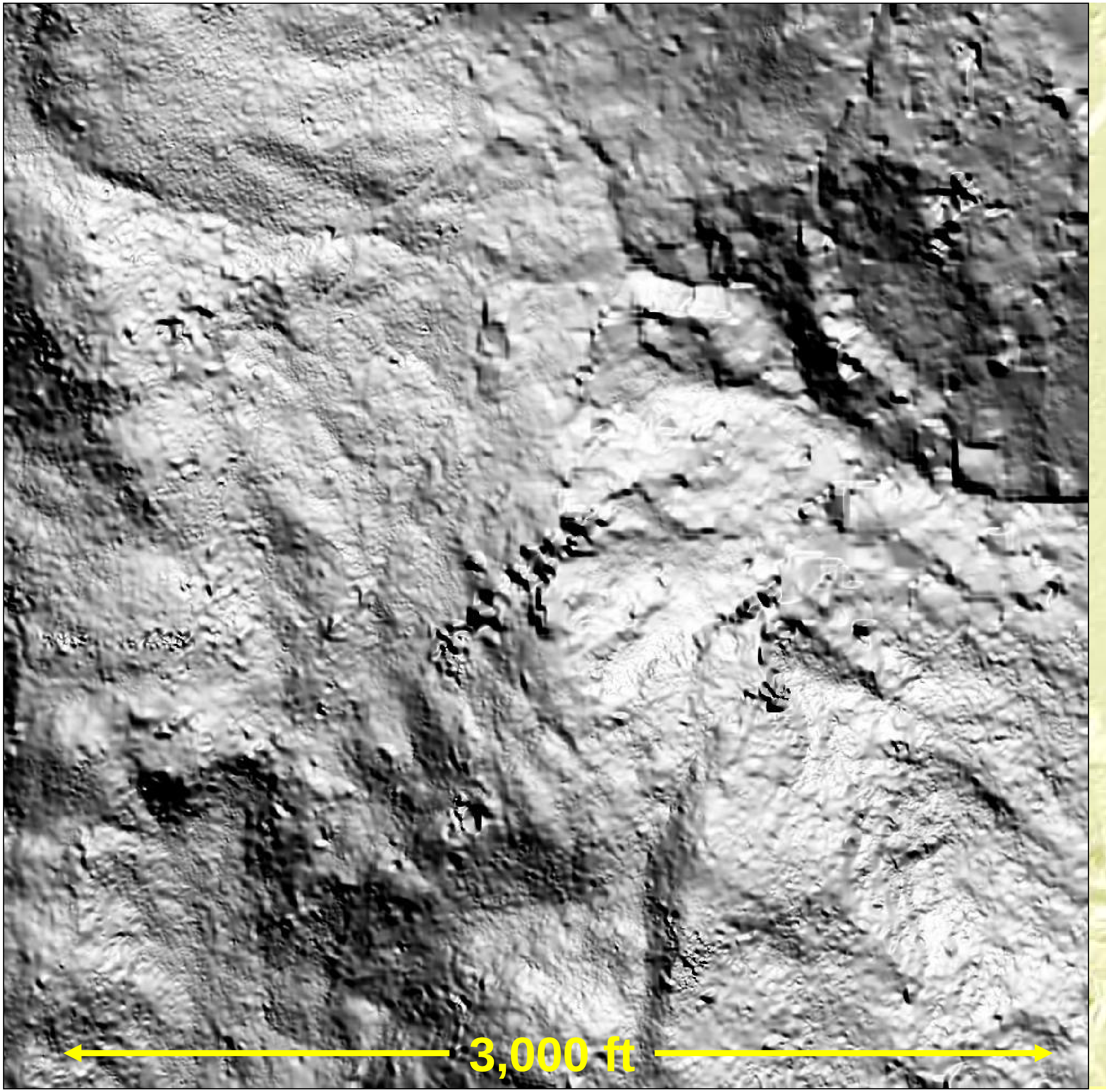
Summary

- Know your data
- Think historically
- Ask questions:
  - How accurate are these data?
  - Do these data adequately sample the landscape?
  - What ***is*** the landscape?
  - How can the landscape be parsed?
  - What was the interplay of process over space and time in the landscape?



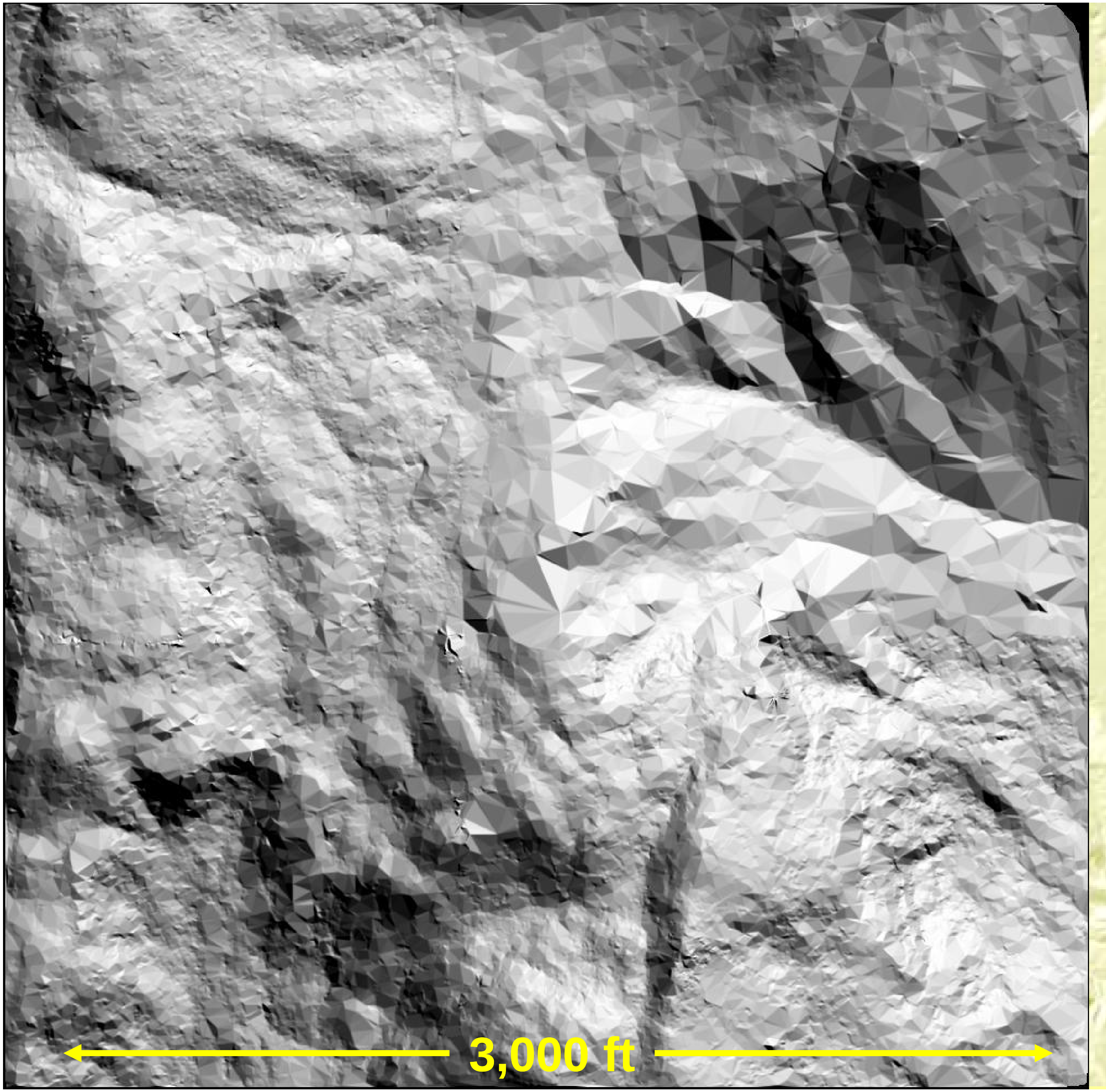
~1 pulse/m^2, leaf-on

Ground points interpolated to 3 ft DEM with ArcInfo Grid IDW



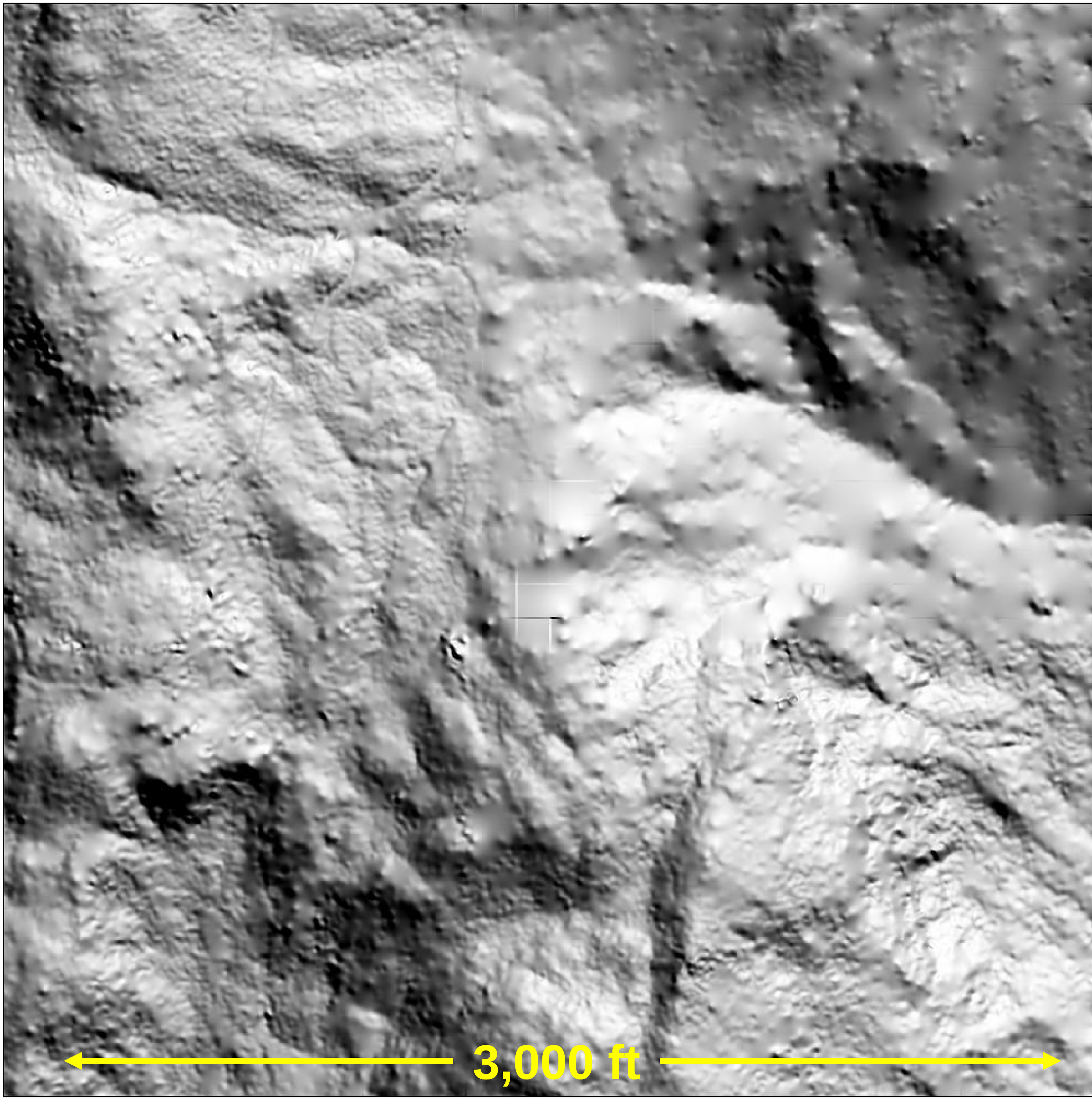
~1 pulse/m^2, leaf-on

Ground points interpolated to 3 ft DEM with ArcInfo Grid SPLINE



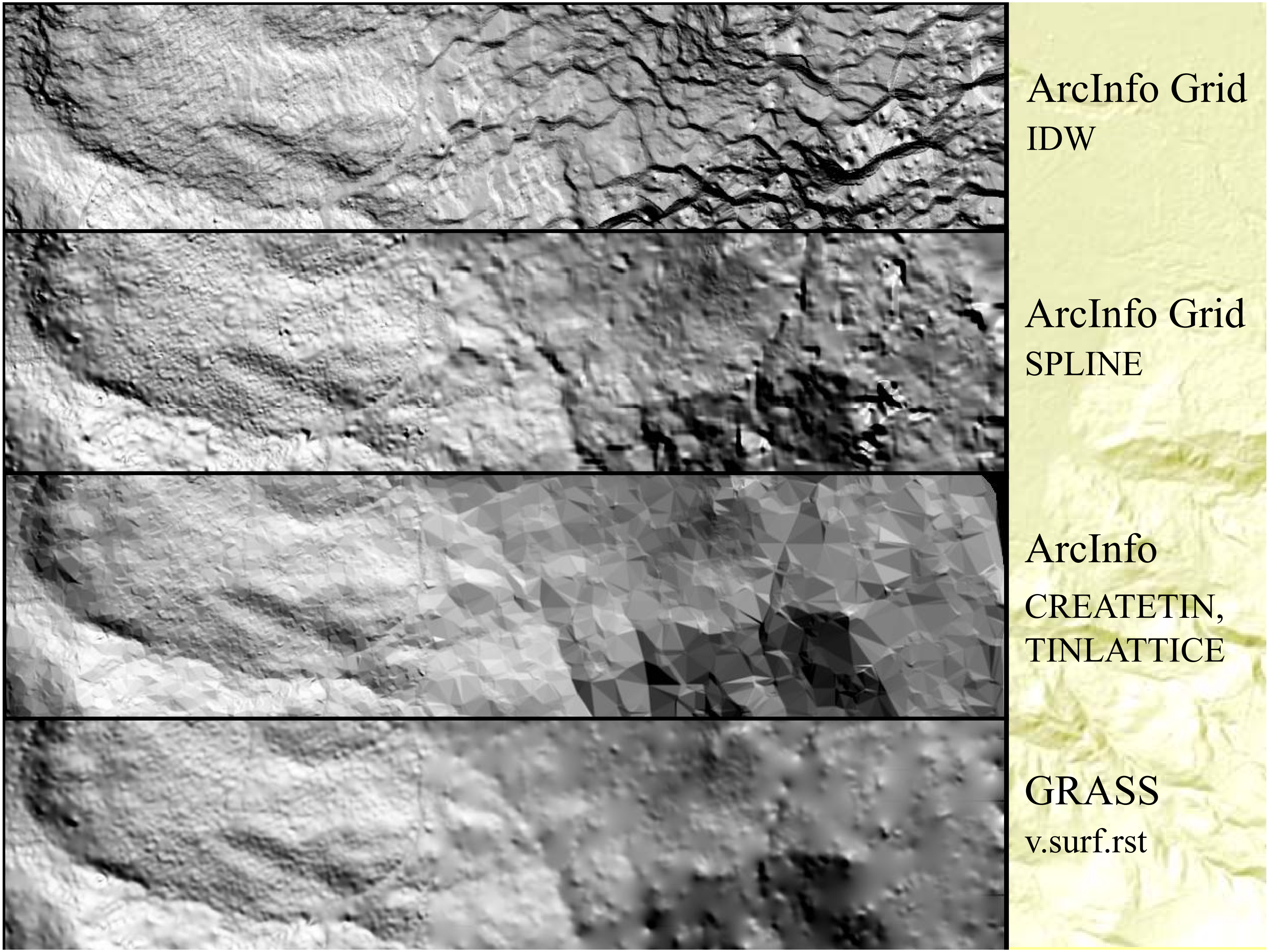
~1 pulse/m^2, leaf-on

Ground points interpolated to 3 ft DEM with ArcInfo CREATETIN, TINLATTICE



~1 pulse/m^2, leaf-on

Ground points interpolated to 3 ft DEM with GRASS v.surf.rst


ArcInfo Grid
IDW
ArcInfo Grid
SPLINE
ArcInfo
CREATETIN,
TINLATTICE
GRASS
v.surf.rst

edges image

```
hue = (170-(dem div A)*B) mod 360
```

A- number of elevation units in one hue step

B- size of color jump between hue steps

```
sat = 40

slope(dem)<=40:
    val=99-99*sqrt(slope(dem)/40)
slope(dem)>40:
    val=0
```