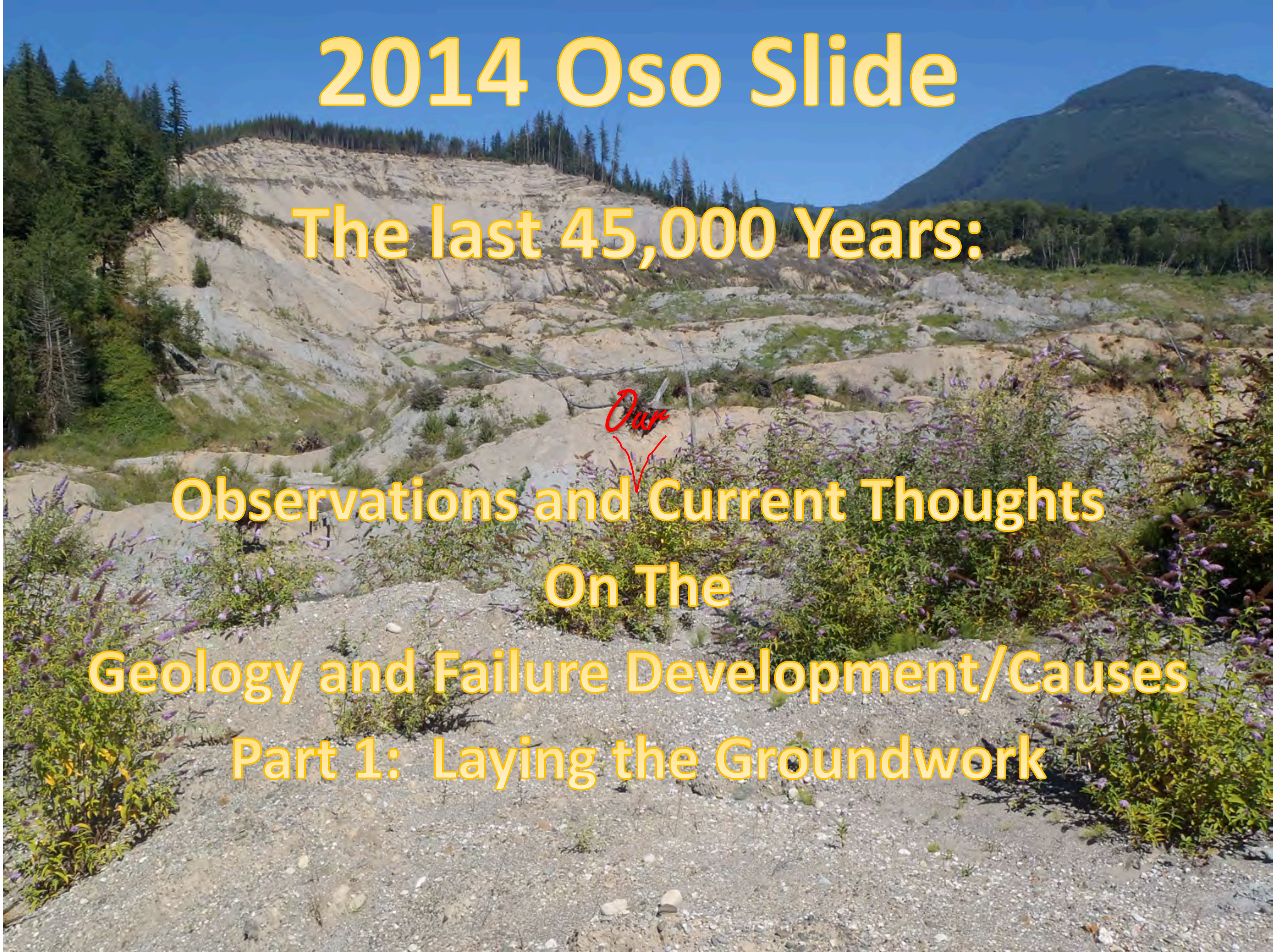


2014 Oso Slide

The last 45,000 Years:

Our Observations and Current Thoughts On The Geology and Failure Development/Causes

Part 1: Laying the Groundwork

What, When, and Where:

Saturday, March 22nd, 2014
around 10:37AM

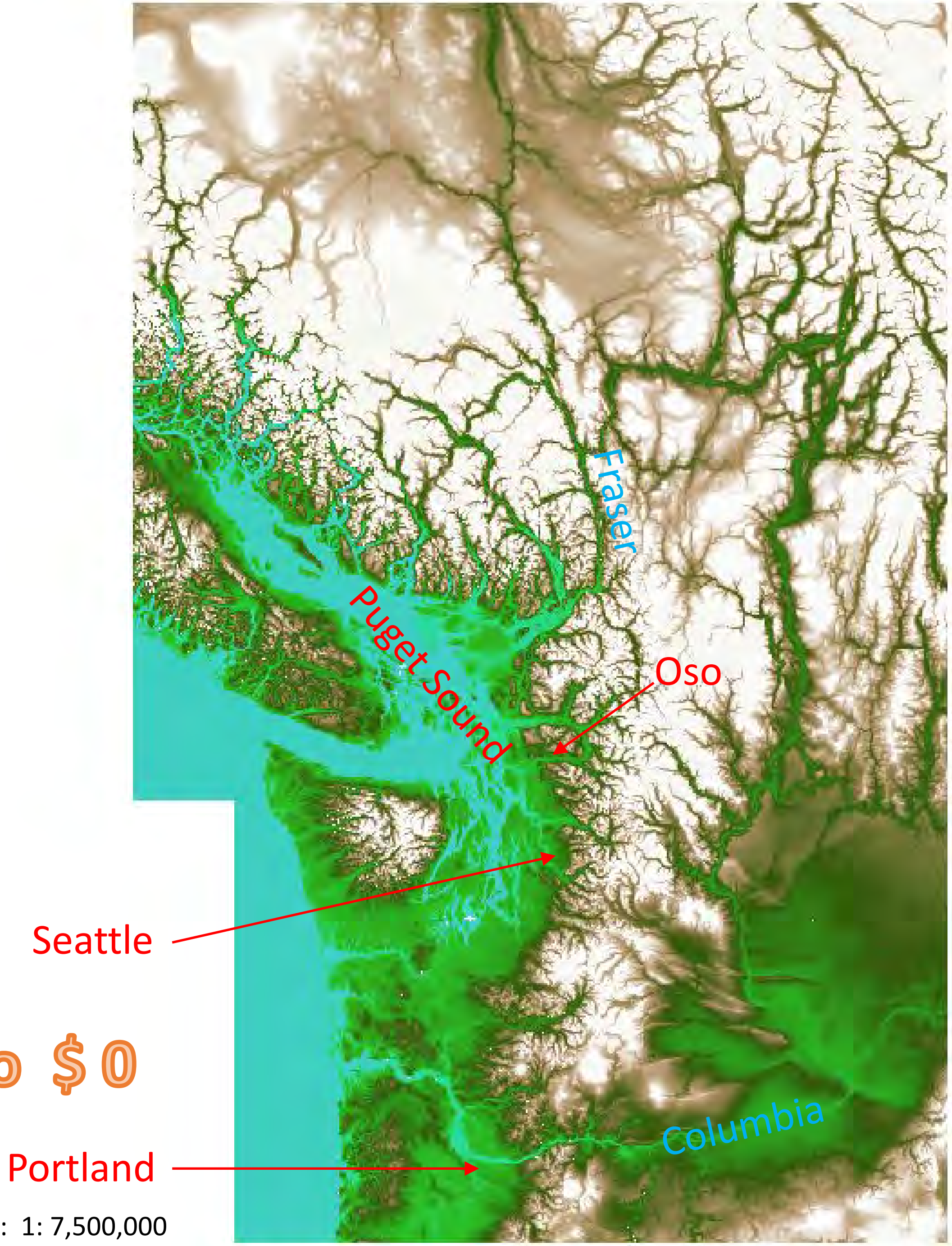
Lasted Approximately 2 Minutes

Largest Slide Disaster in US History

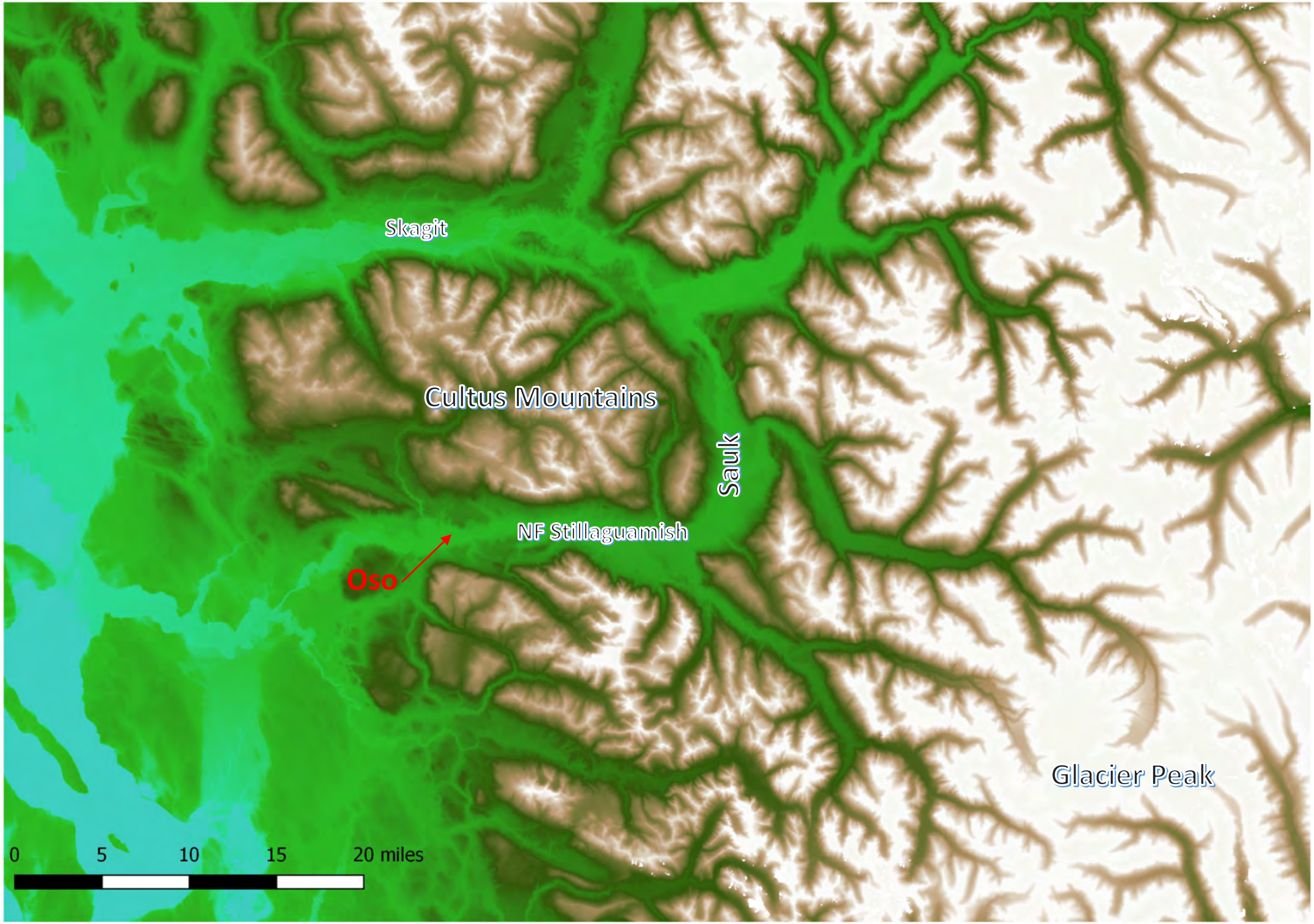
Killed 43 People

$ 71.5 M in Settlements:

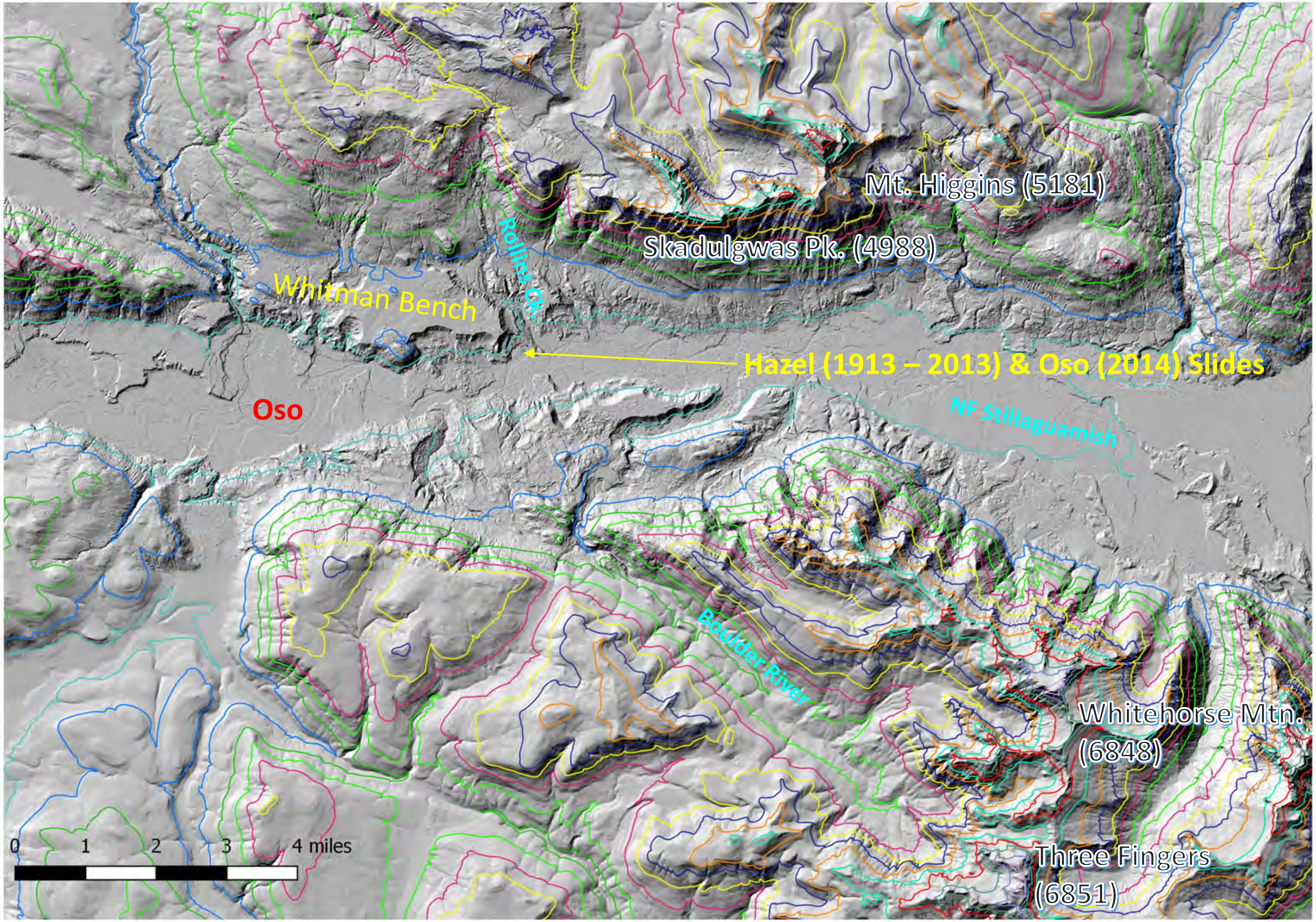
State $ 60 M, Grandy Lake $ 11.5 M, SnoCo $ 0

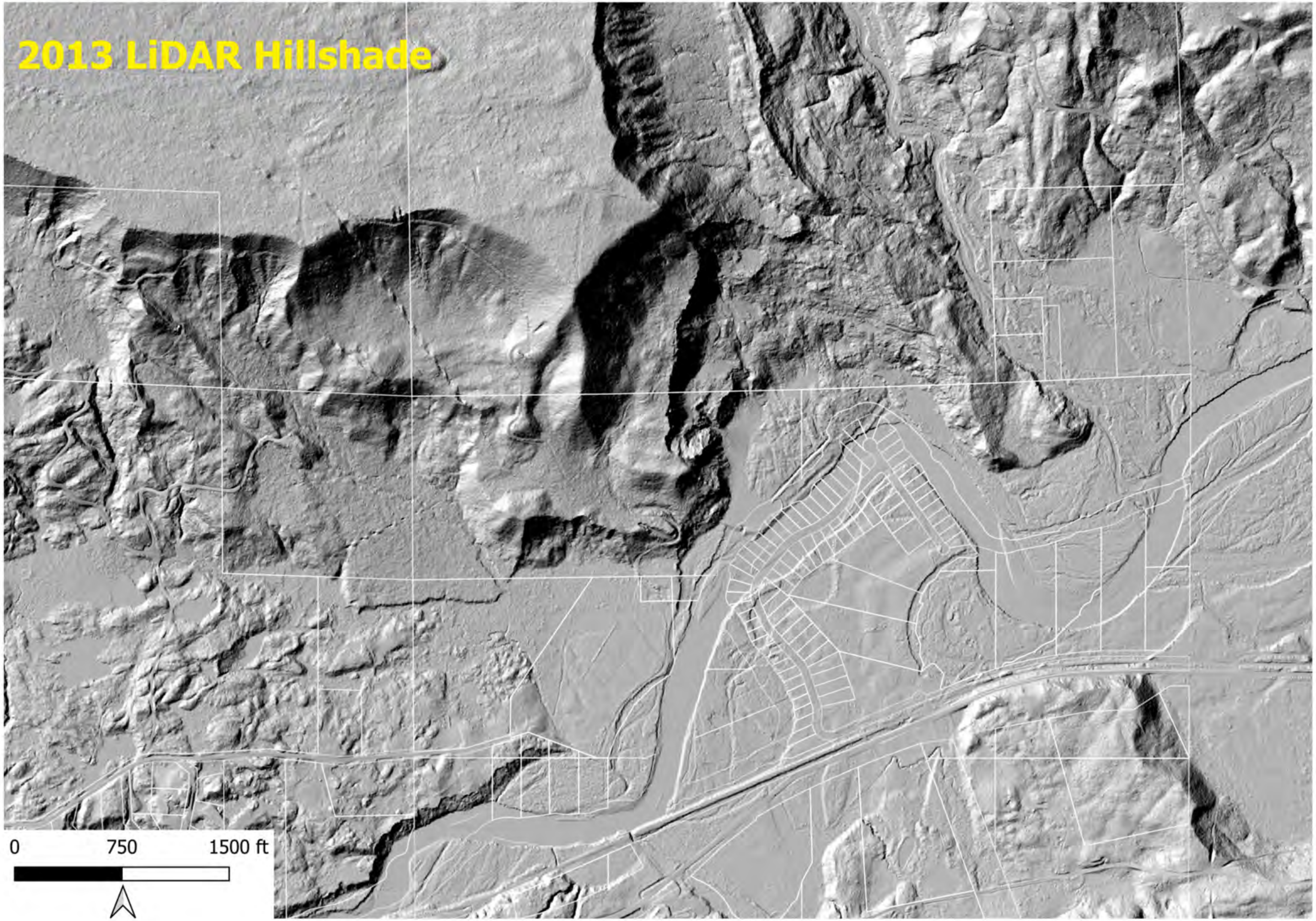


Scale: 1: 7,500,000

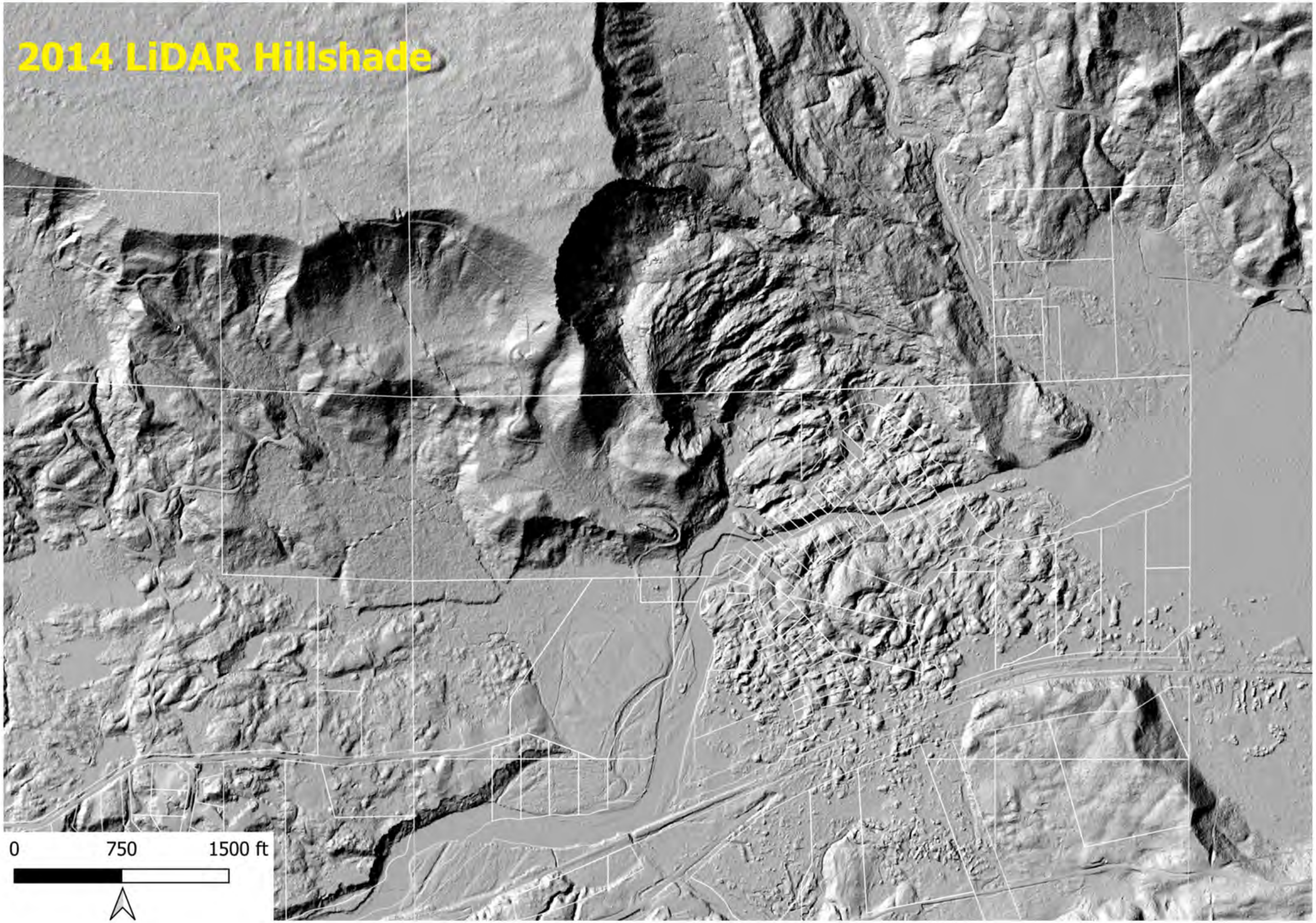


Skagit
Cultus Mountains
Sauk
NF Stillaguamish
Oso
Glacier Peak
0
5
10
15
20 miles

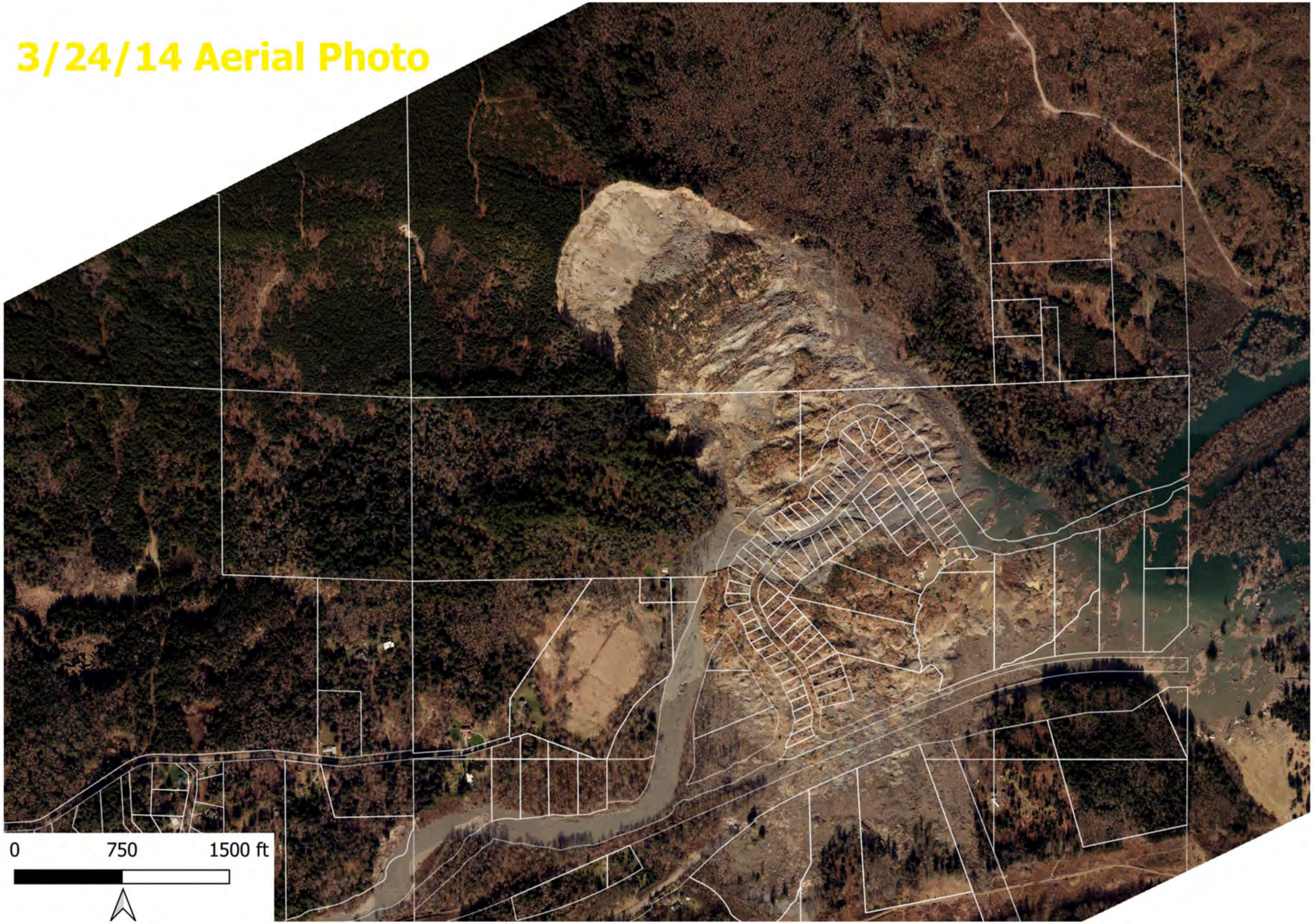

Mt. Higgins (5181)
Skadulgwas Pk. (4988)
Rollins Ck.
Whitman Bench
Hazel (1913 – 2013) & Oso (2014) Slides
Oso
NF Stillaguamish
Boulder River
Whitehorse Mtn. (6848)
Three Fingers (6851)
0 1 2 3 4 miles



2013 LiDAR Hillshade
0
750
1500 ft


2014 LiDAR Hillshade
0
750
1500 ft


2012 Aerial Photo
0
750
1500 ft


3/24/14 Aerial Photo
0
750
1500 ft

https://www.youtube.com/watch?v=UUFByAwcGs0&t=14s


22-MAR-2014
11:22:33
FLIR
SYSTEMS
2:15 / 21:26


22-MAR-2014
11:25:57
FLIR
SYSTEMS
5:39 / 21:26

22-MAR-2014
11:31:15
FLIR SYSTEMS
10:58 / 21:26


22-MAR-2014
11:27:48
FLIR
SYSTEMS
7:31 / 21:26


22-MAR-2014
11:30:22
FLIR SYSTEMS
10:05 / 21:26

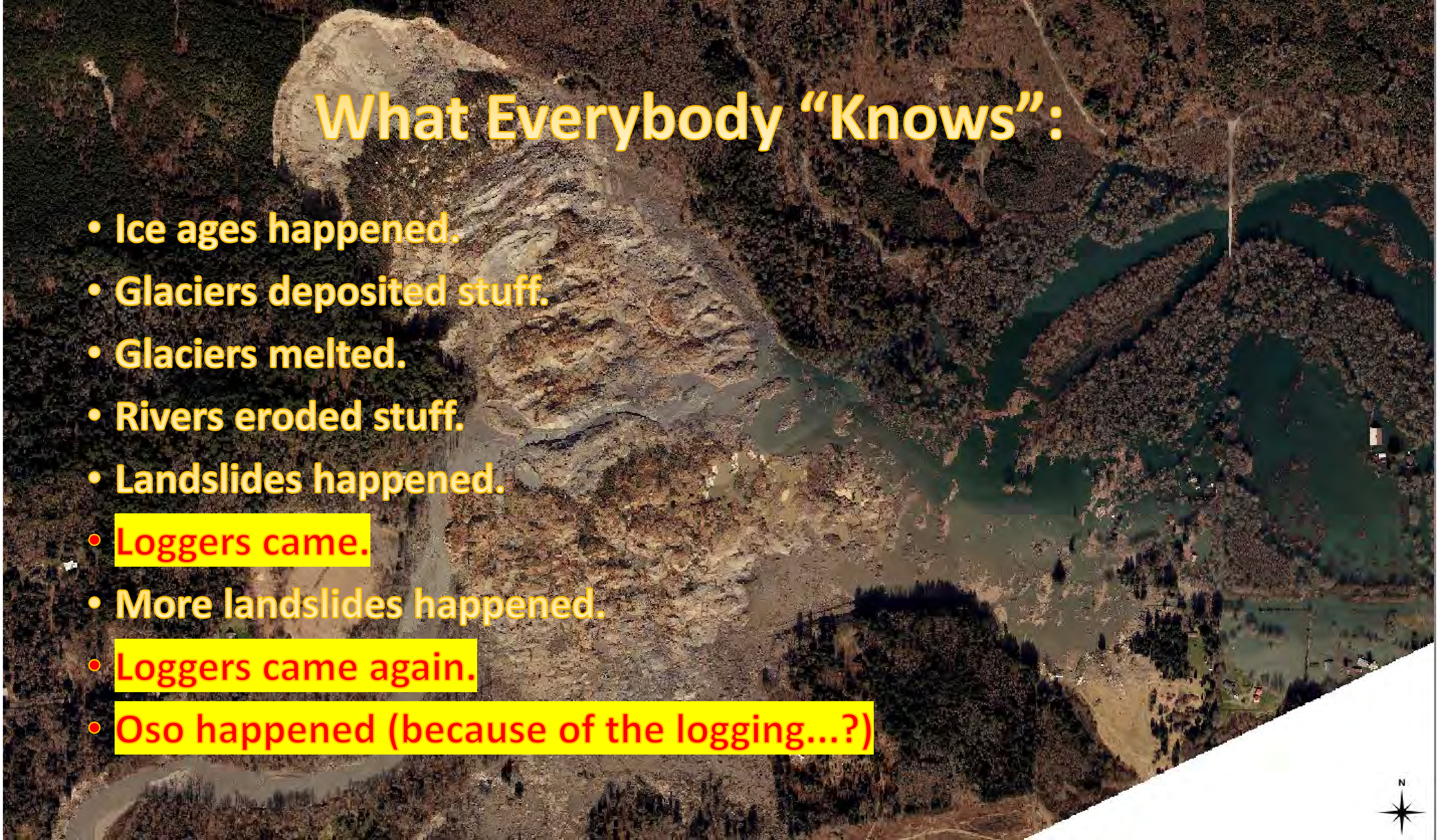
Why Did This Happen?

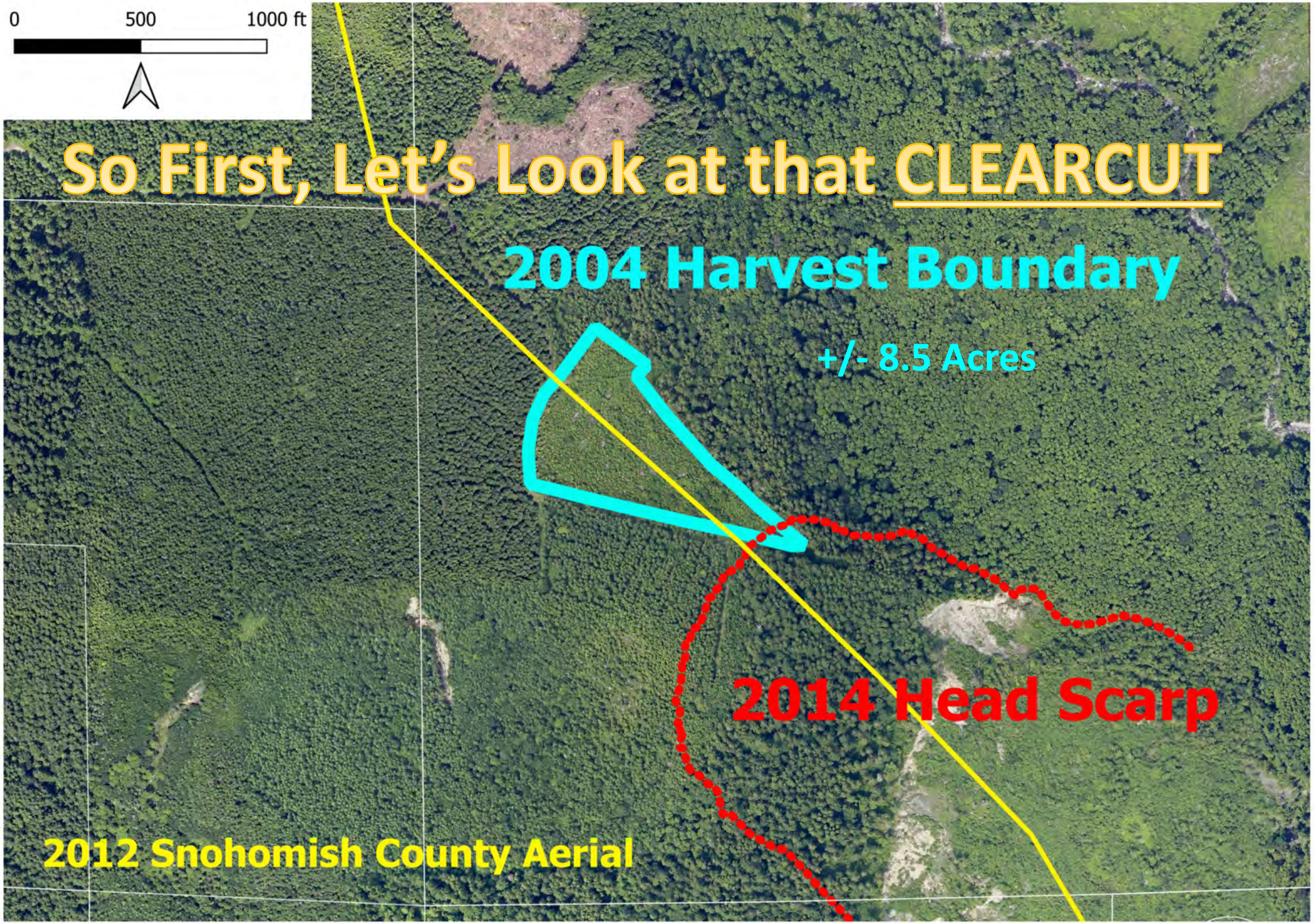
The day after the event, some journalists (in newspapers, radio, and TV) started implying that this disaster was related at least in part to an 8.5-acre clearcut performed 9 years prior to the event.

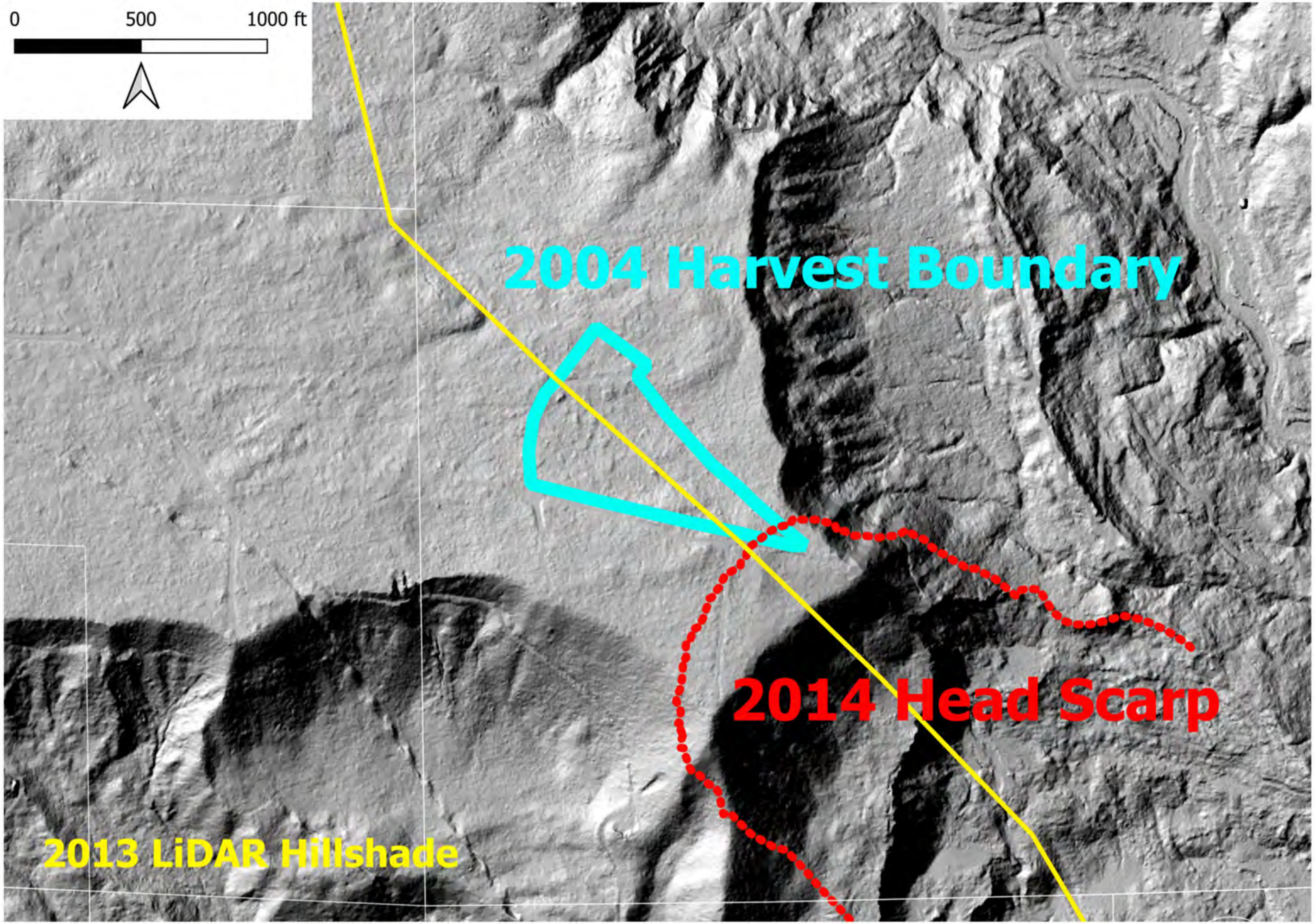
The regulatory bodies (DNR, Board of Forestry) have publicly reviewed and changed their guidelines for slope stability assessments for timber harvest in the wake of the disaster. This is clearly an attempt to do SOMETHING. The public has perceived this as a tacit acknowledgement (implication) that forestry issues were indeed a significant part of the problem.

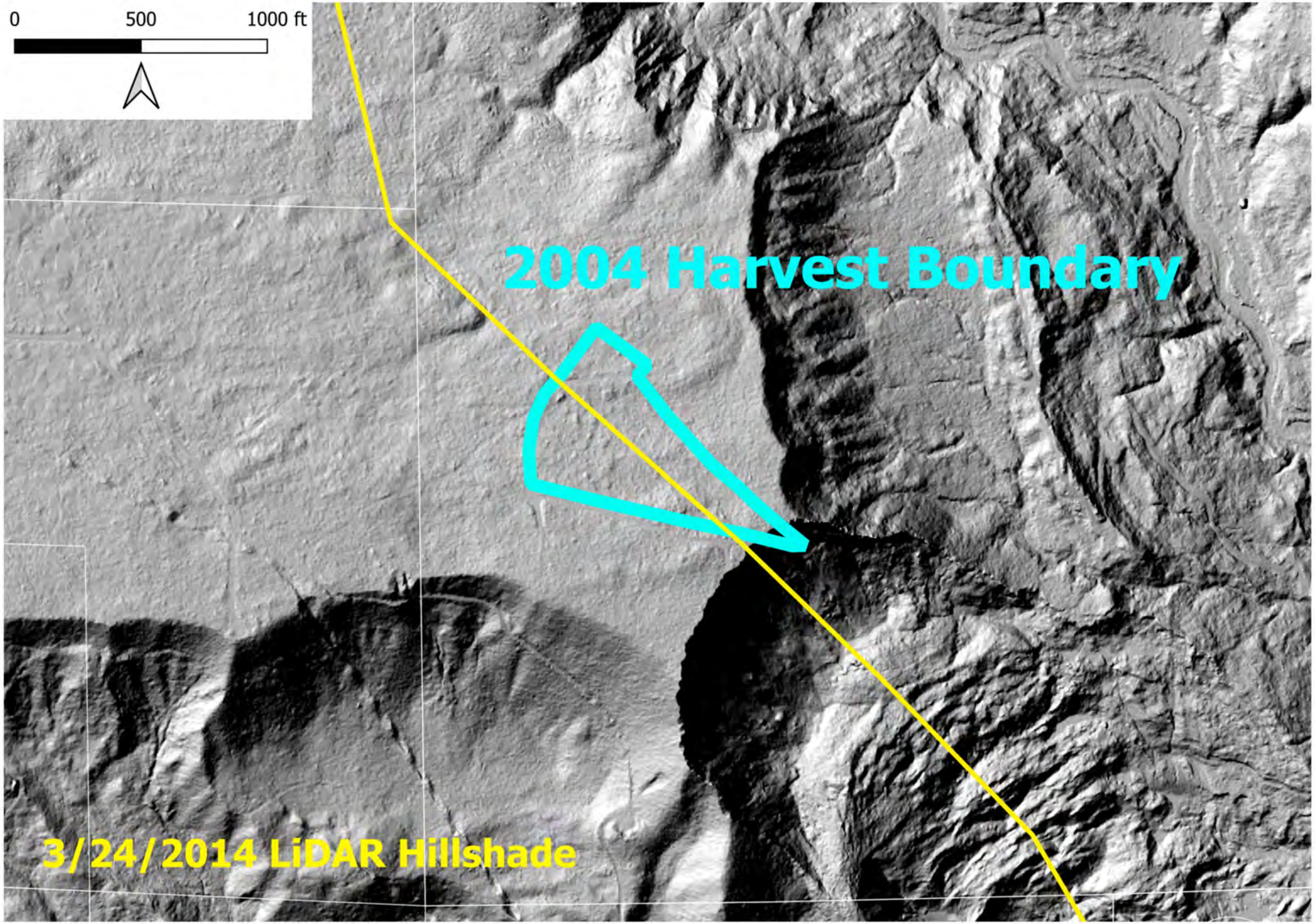
What Everybody "Knows":

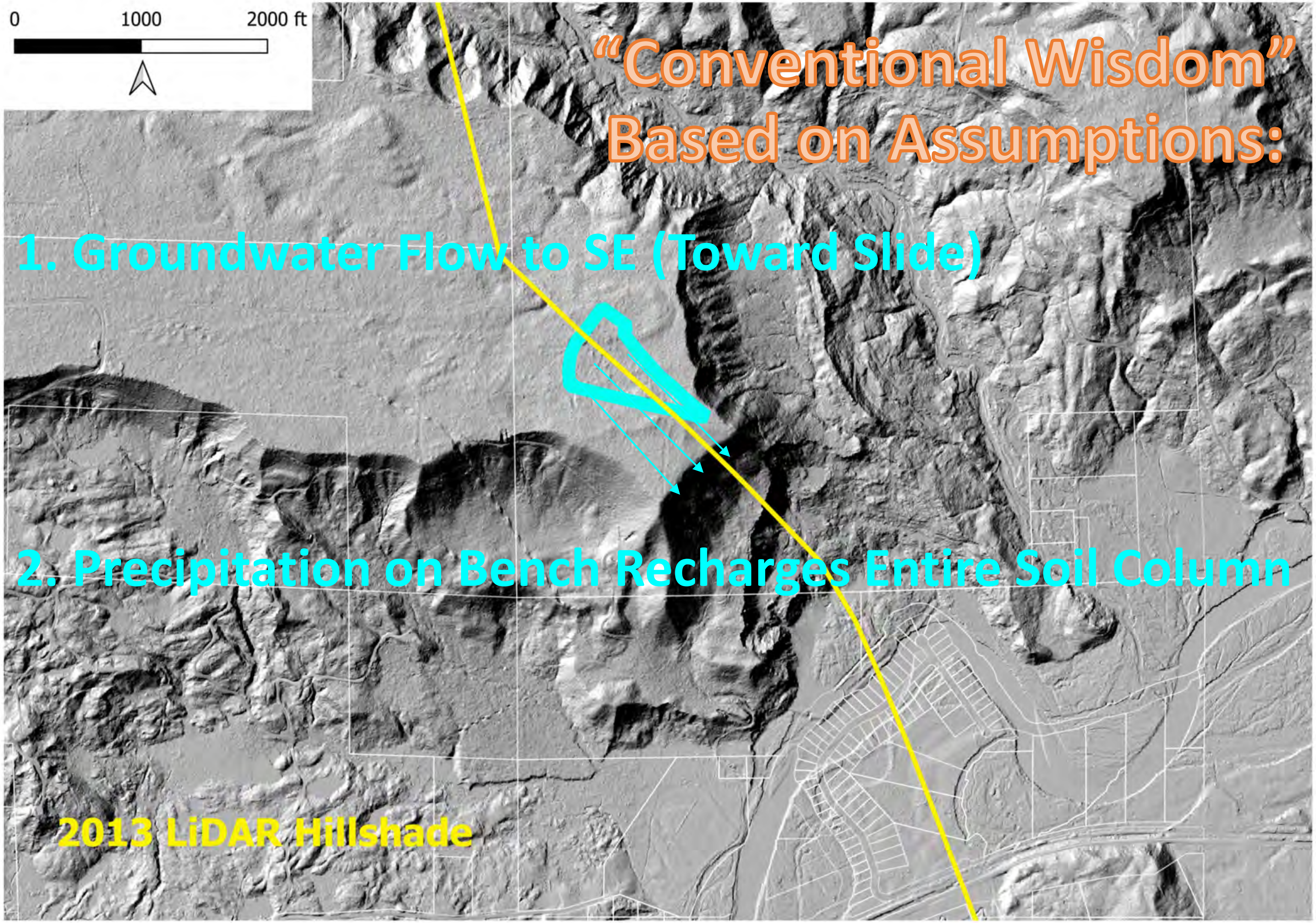
- Ice ages happened.
- Glaciers deposited stuff.
- Glaciers melted.
- Rivers eroded stuff.
- Landslides happened.
- Loggers came.
- More landslides happened.
- Loggers came again.
- Oso happened (because of the logging...?)




0
500
1000 ft
So First, Let's Look at that CLEARCUT
2004 Harvest Boundary
+/- 8.5 Acres
2014 Head Scarp
2012 Snohomish County Aerial

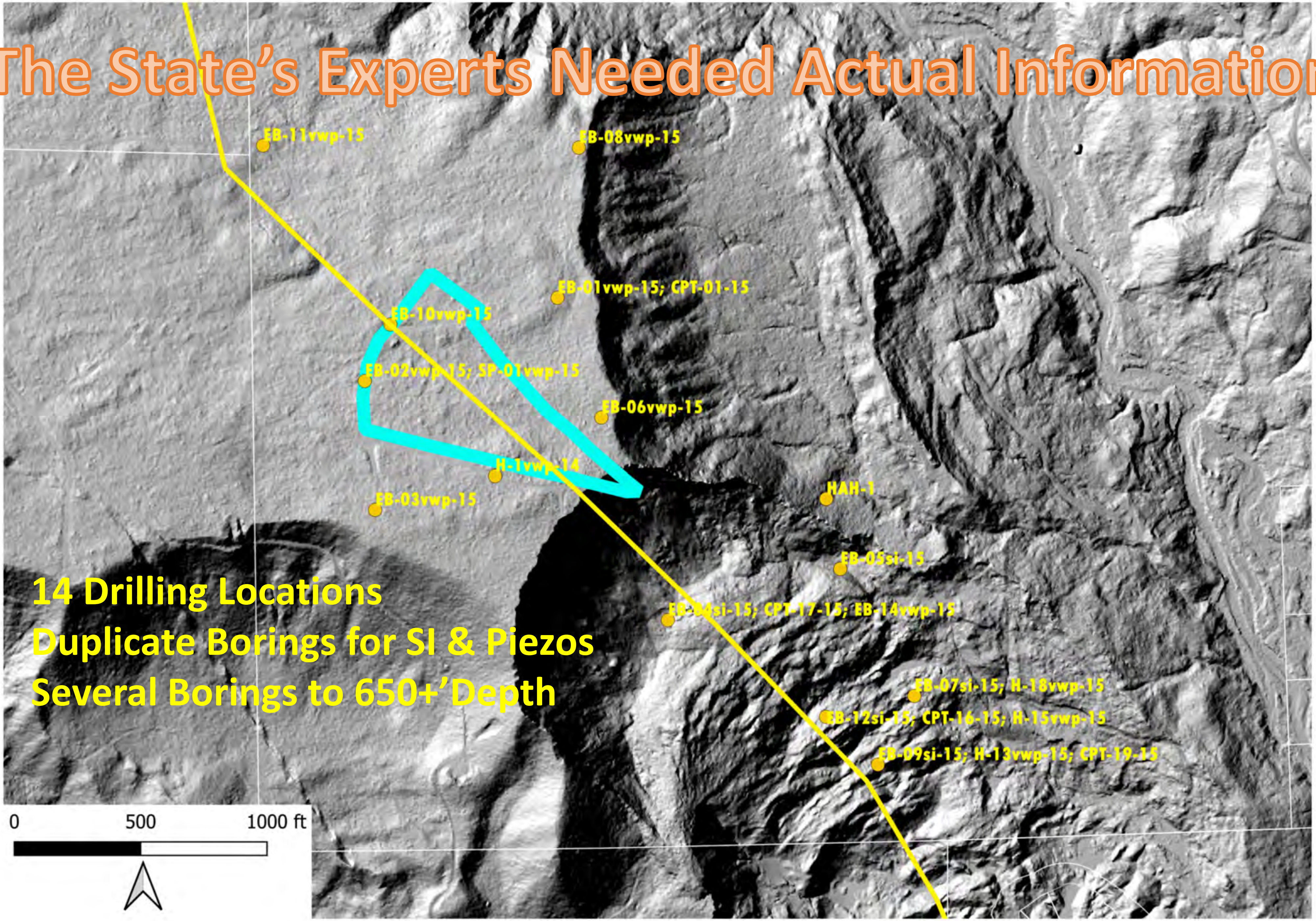

0
500
1000 ft
2004 Harvest Boundary
2014 Head Scarp
2013 LiDAR Hillshade


0
500
1000 ft
2004 Harvest Boundary
3/24/2014 LiDAR Hillshade



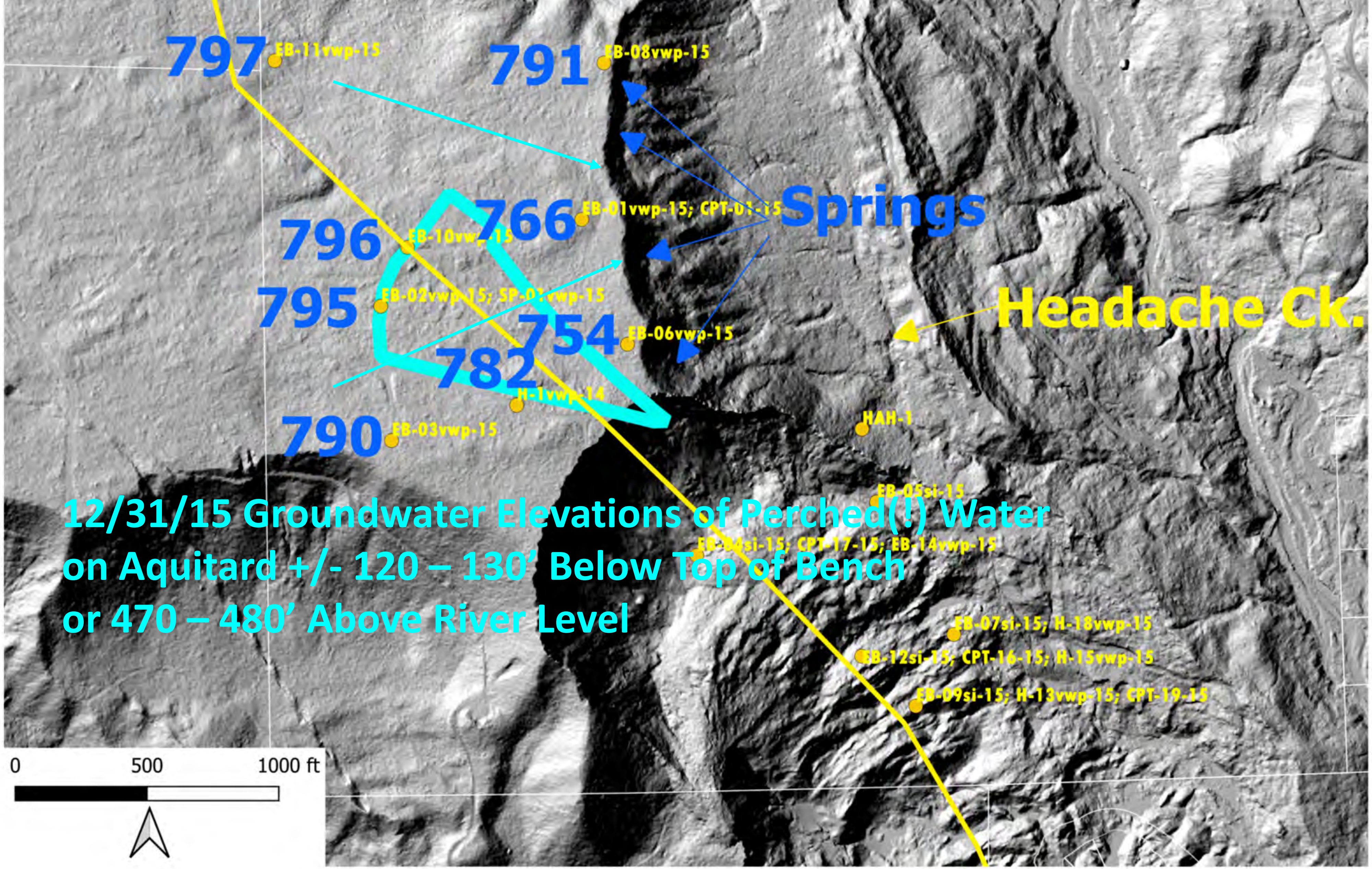
0
1000
2000 ft
"Conventional Wisdom" Based on Assumptions:
1. Groundwater Flow to SE (Toward Slide)
2. Precipitation on Bench Recharges Entire Soil Column
2013 LiDAR Hillshade

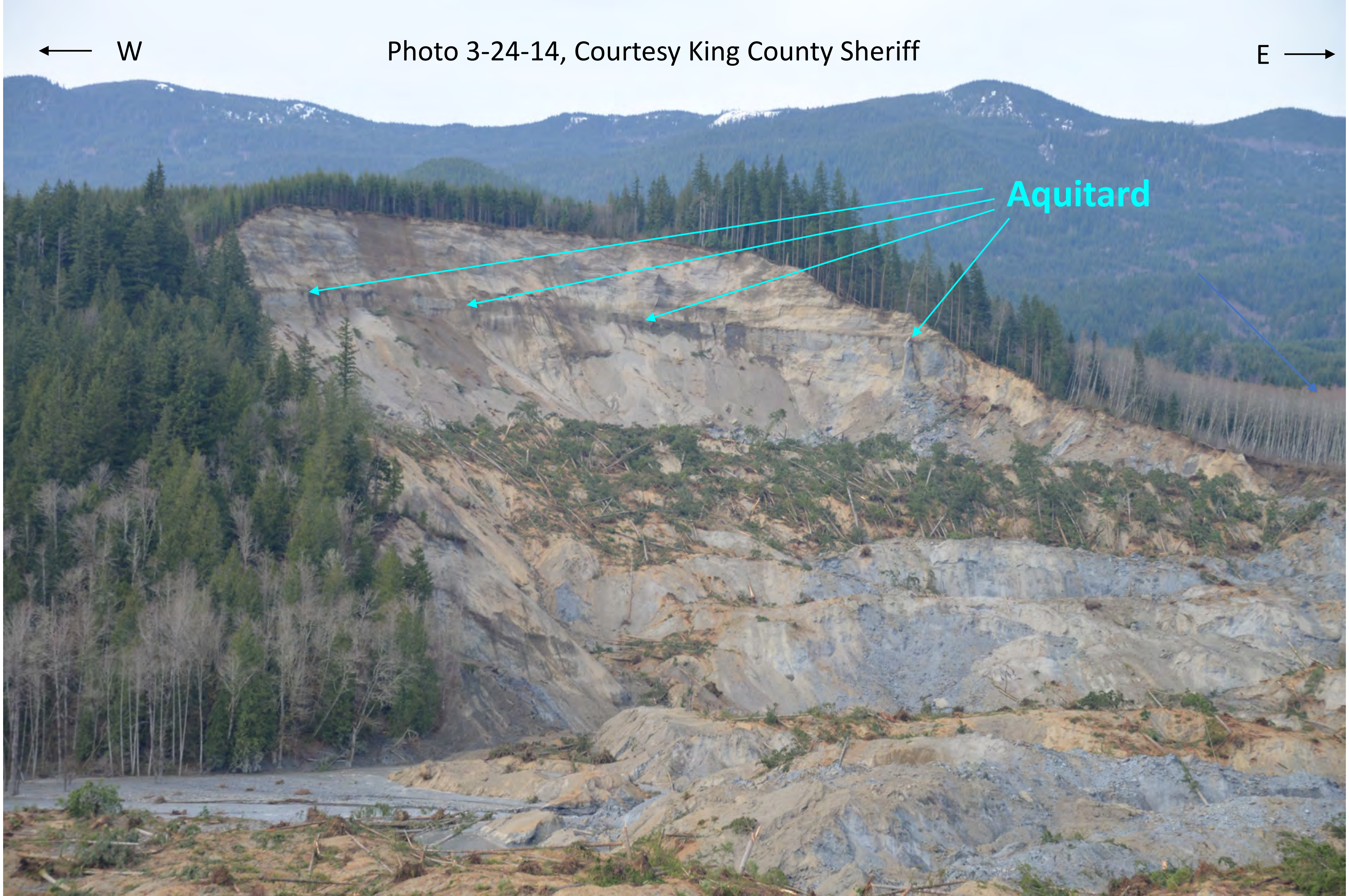
The State's Experts Needed Actual Information



14 Drilling Locations
Duplicate Borings for SI & Piezos
Several Borings to 650+' Depth

Actual Groundwater Flow to ENE and ESE:



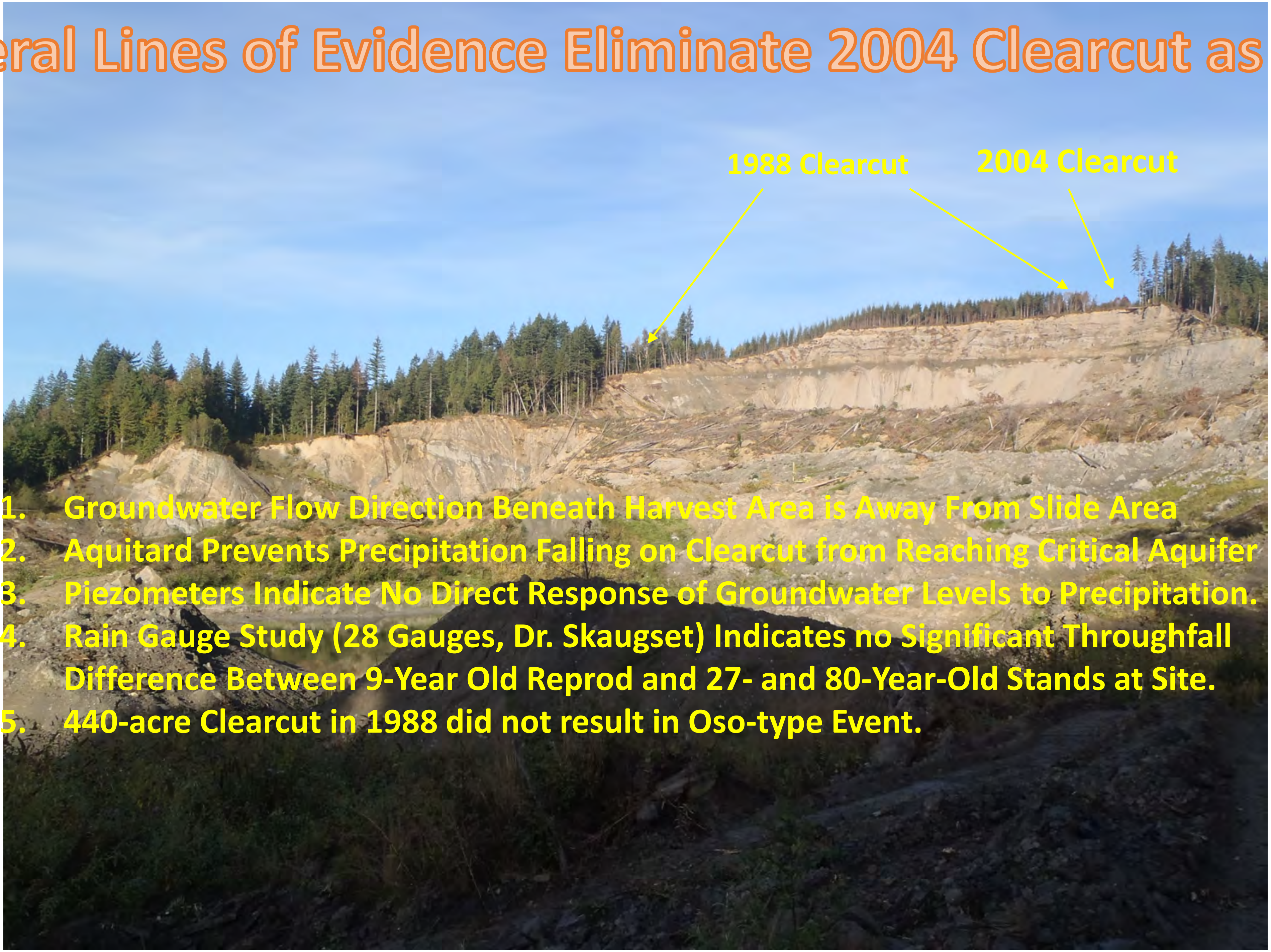


W
Photo 3-24-14, Courtesy King County Sheriff
E
Aquitard

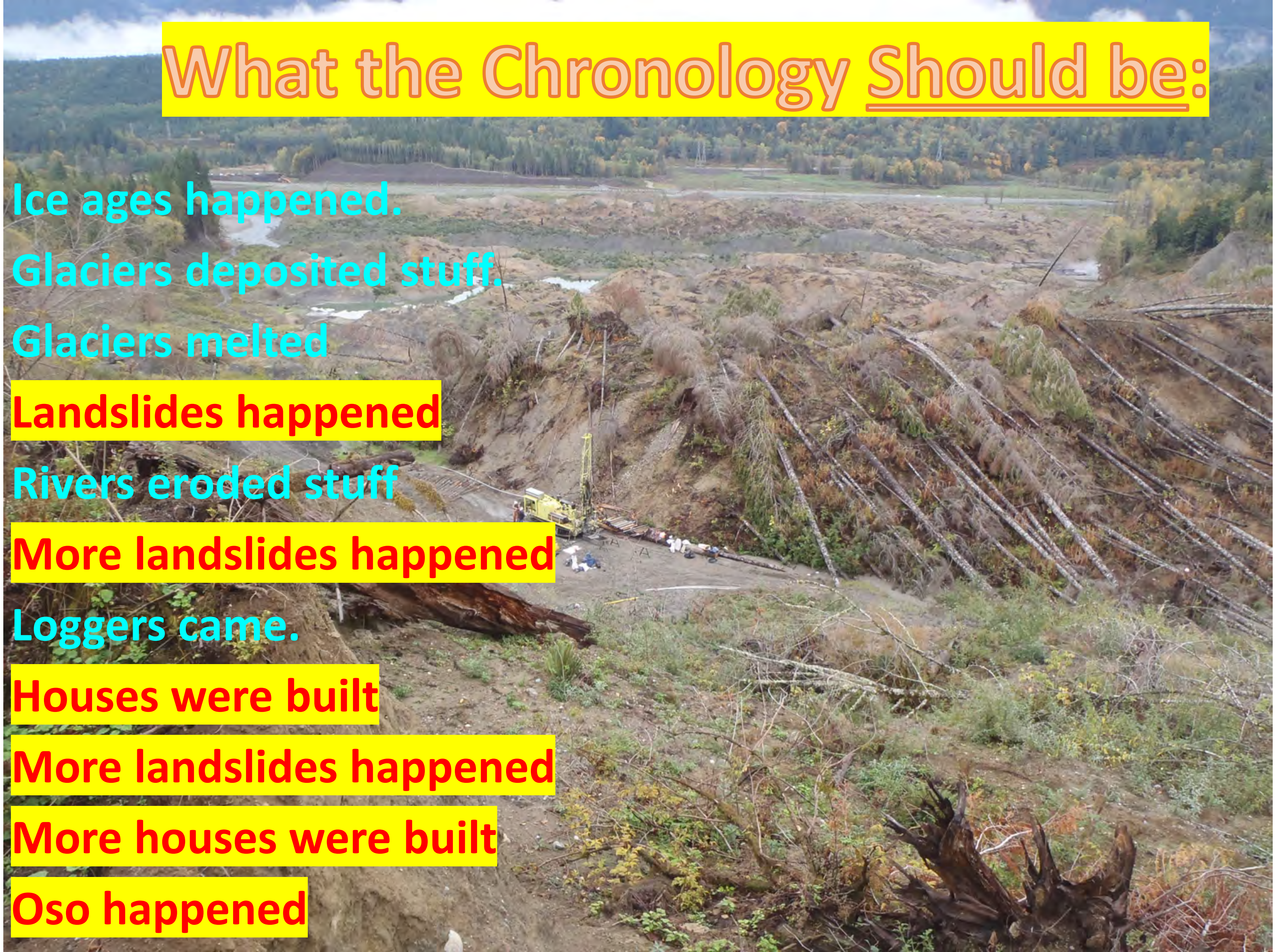

3/25/14 Photo Courtesy Snohomish County
Eastern Head Scarp
Aquitard
Even Only 3 Days After the Slide, Just Minor Seeps
SC_C14-048_008788


3/25/14 Photo Courtesy Snohomish County
Western Head Scarp
Aquitard
22.22 x 16.67 in
SC_C14-046_008768

Several Lines of Evidence Eliminate 2004 Clearcut as Cause



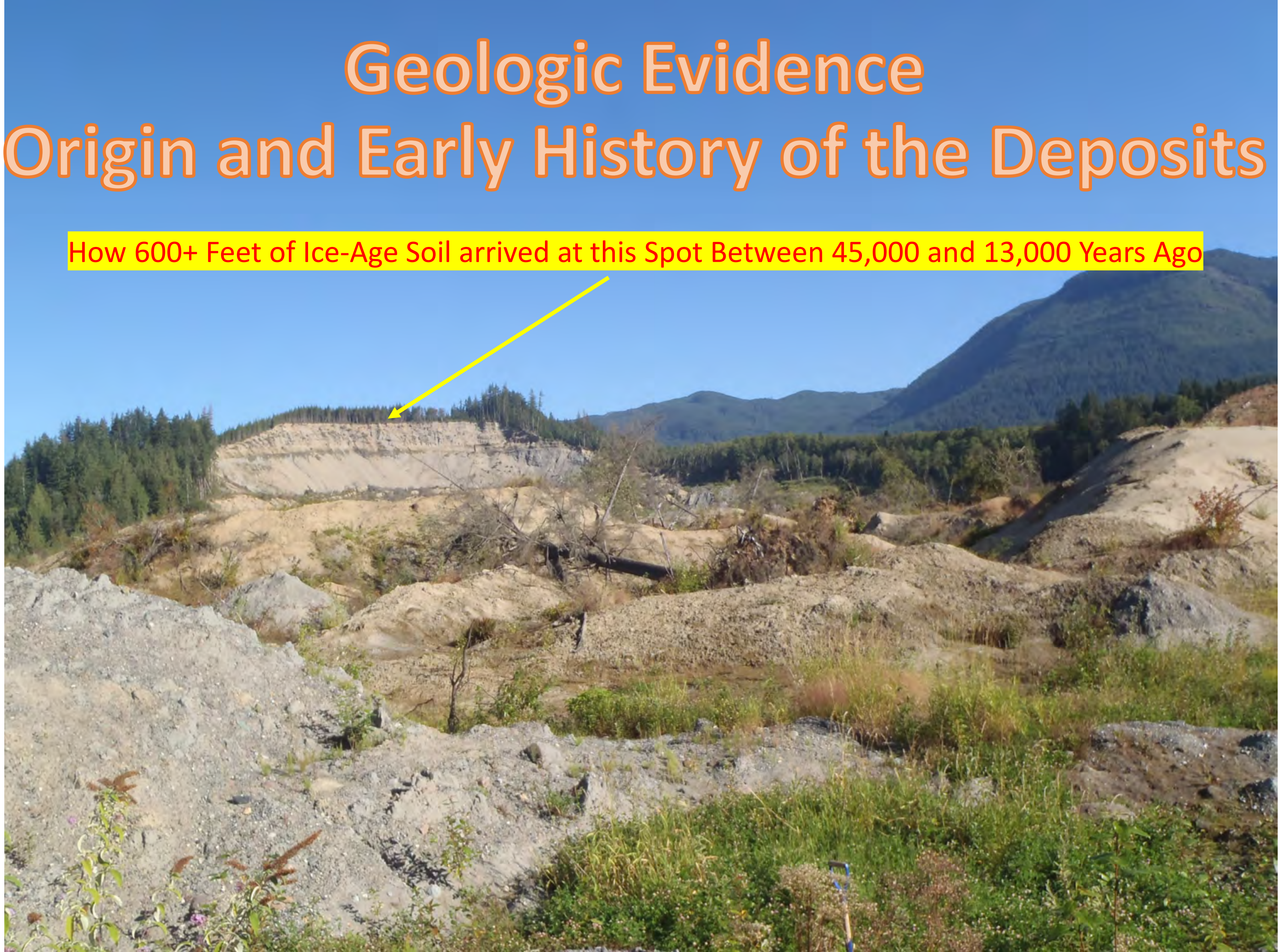
1. Groundwater Flow Direction Beneath Harvest Area is Away From Slide Area
2. Aquitard Prevents Precipitation Falling on Clearcut from Reaching Critical Aquifer
3. Piezometers Indicate No Direct Response of Groundwater Levels to Precipitation.
4. Rain Gauge Study (28 Gauges, Dr. Skaugset) Indicates no Significant Throughfall Difference Between 9-Year Old Reprod and 27- and 80-Year-Old Stands at Site.
5. 440-acre Clearcut in 1988 did not result in Oso-type Event.

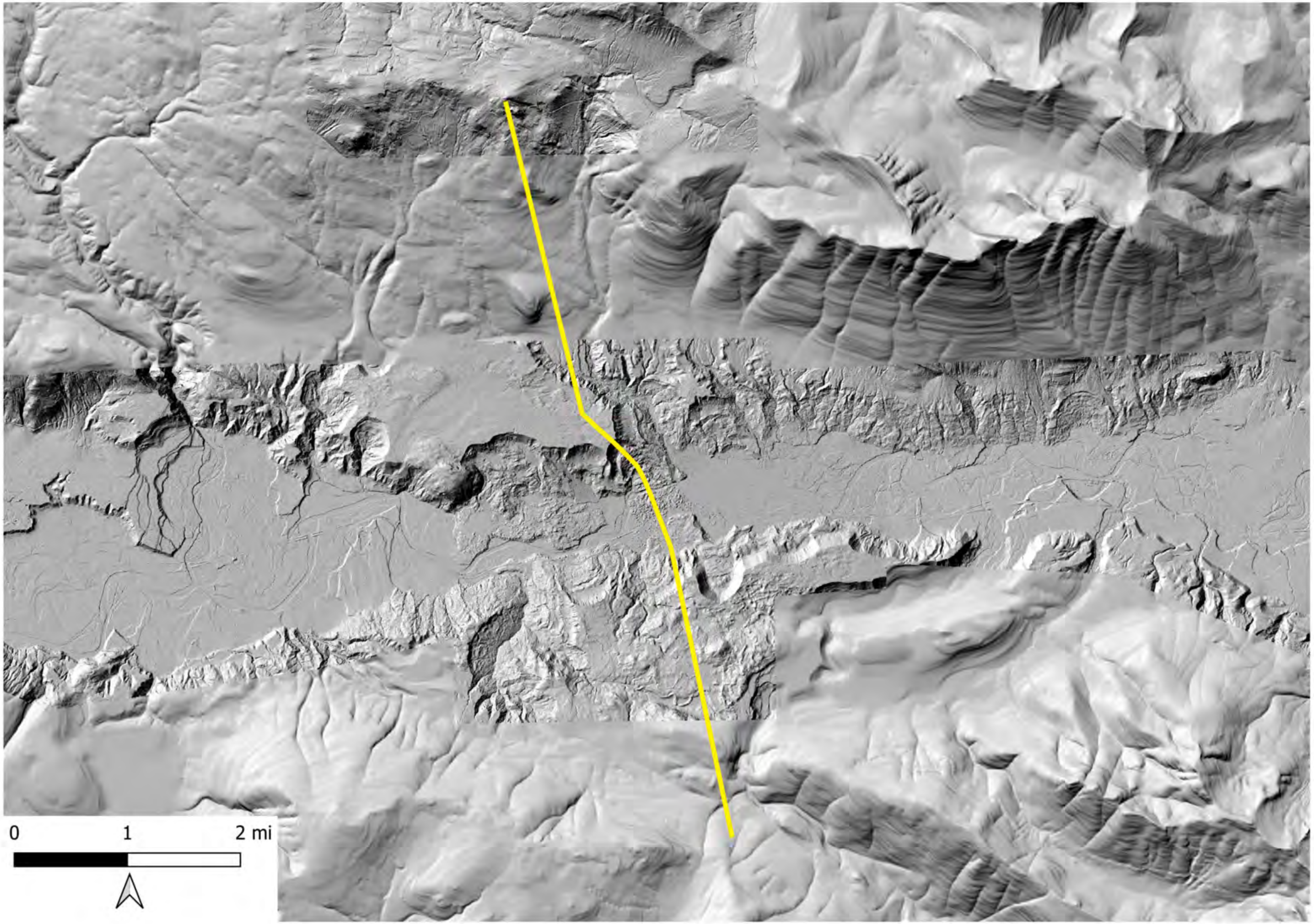


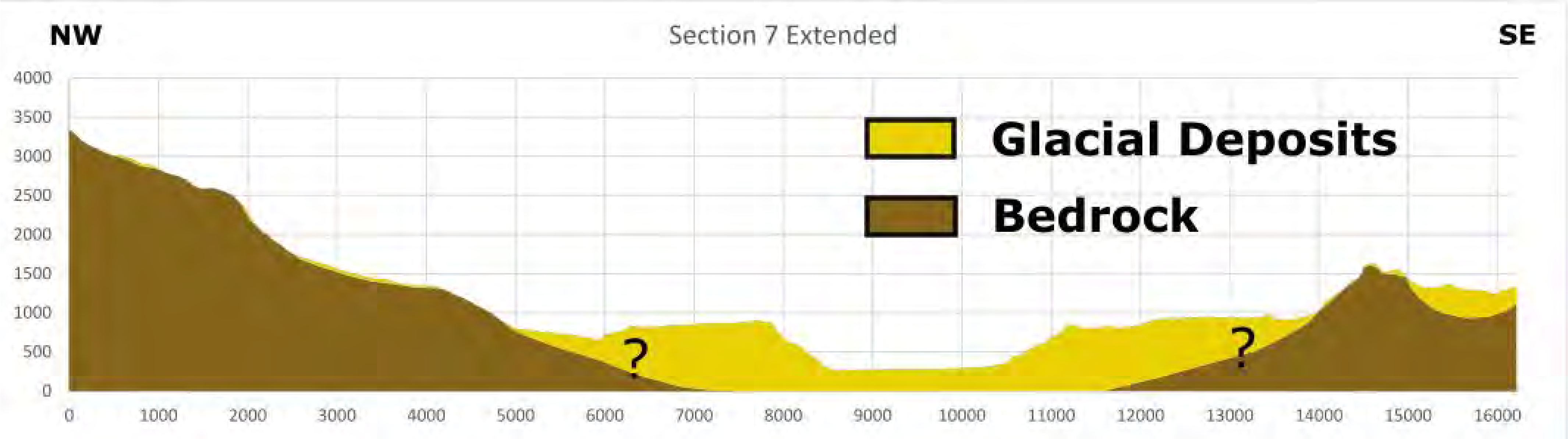
What the Chronology Should be:

- Ice ages happened.
- Glaciers deposited stuff.
- Glaciers melted
- Landslides happened
- Rivers eroded stuff
- More landslides happened
- Loggers came.
- Houses were built
- More landslides happened
- More houses were built
- Oso happened

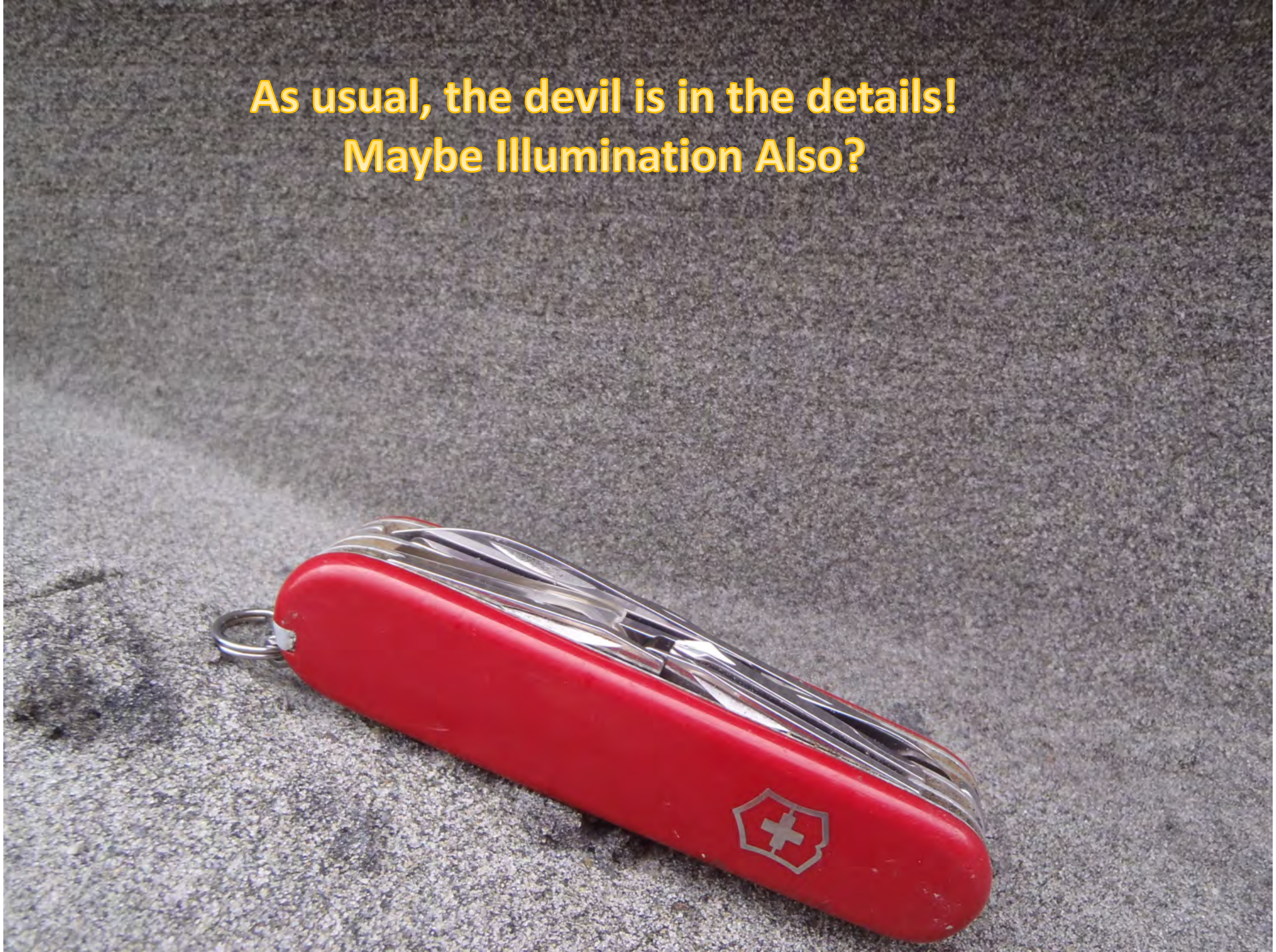
Geologic Evidence
Origin and Early History of the Deposits




0
1
2 mi



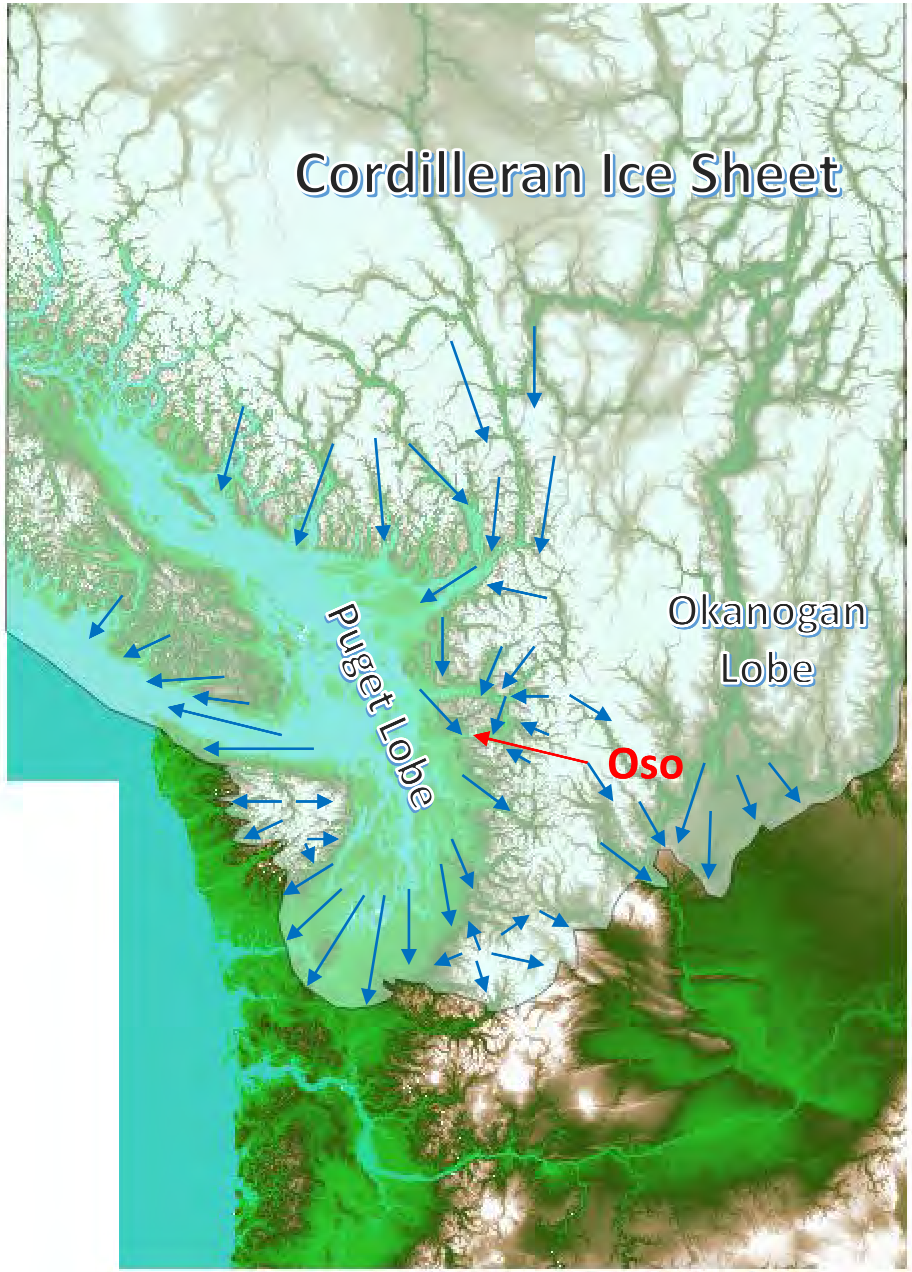
NW
Section 7 Extended
SE
4000
3500
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
Glacial Deposits
Bedrock
?
?

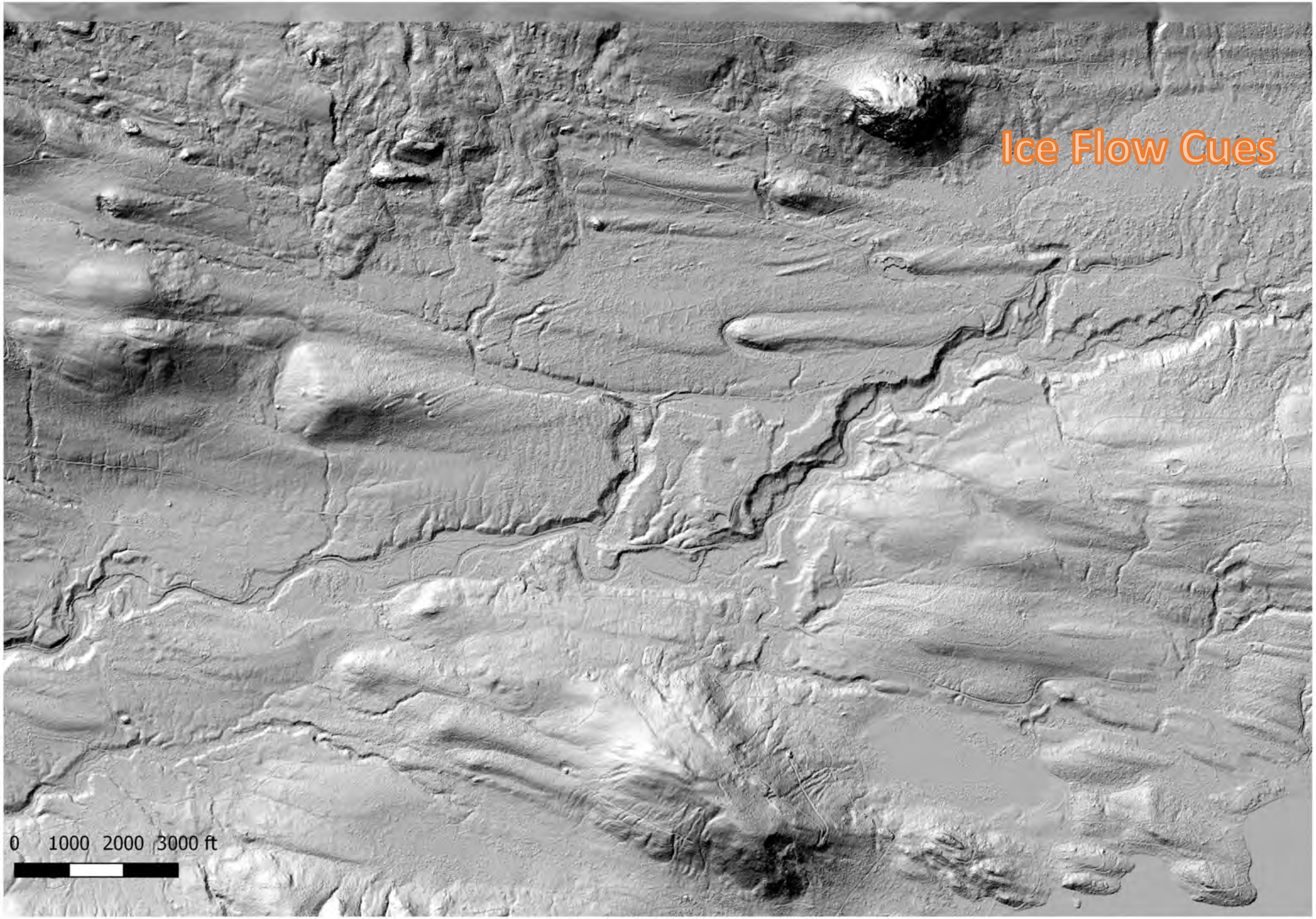

As usual, the devil is in the details!
Maybe Illumination Also?

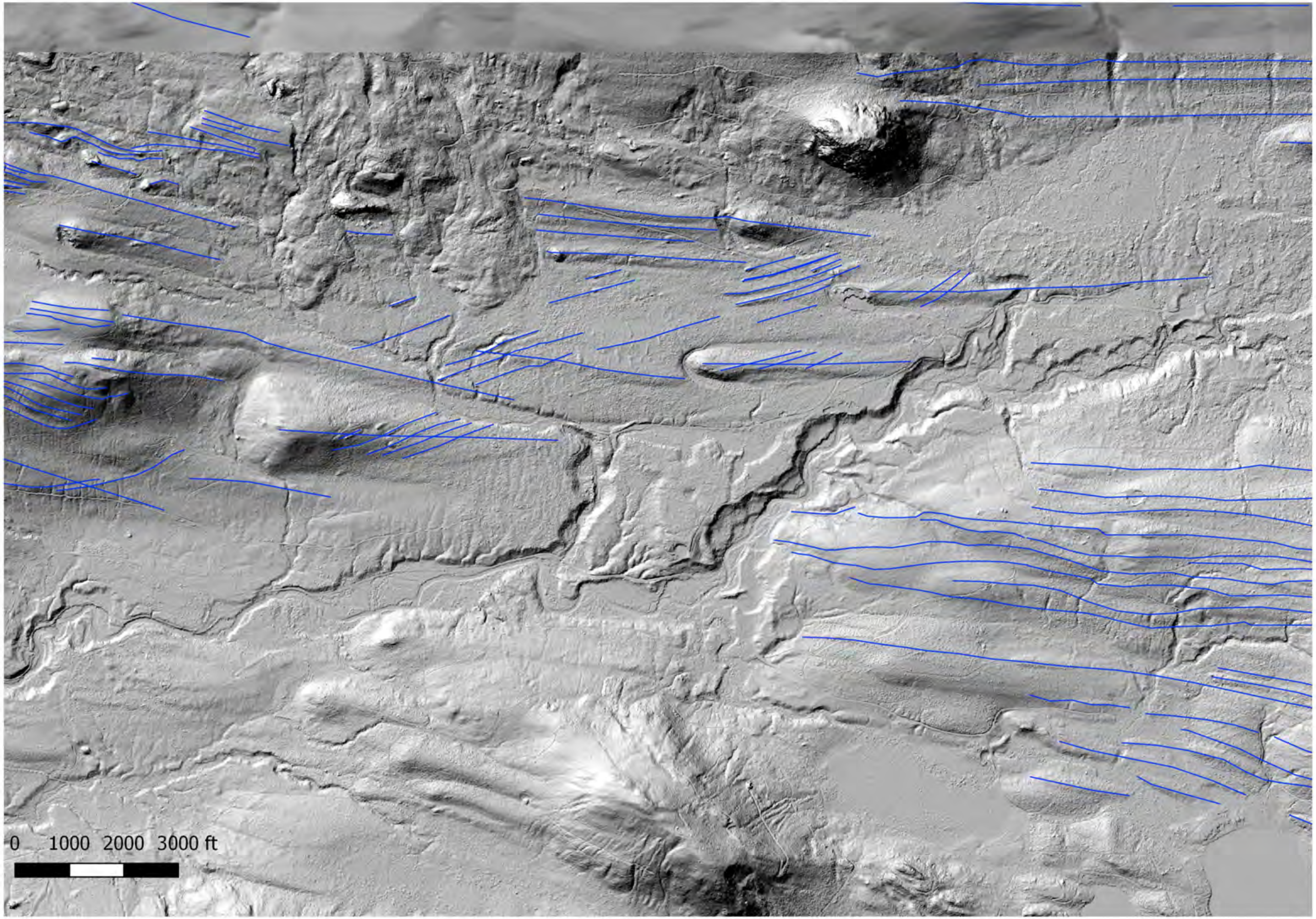
Ice Sheets 24,000 to 13,000 YBP:

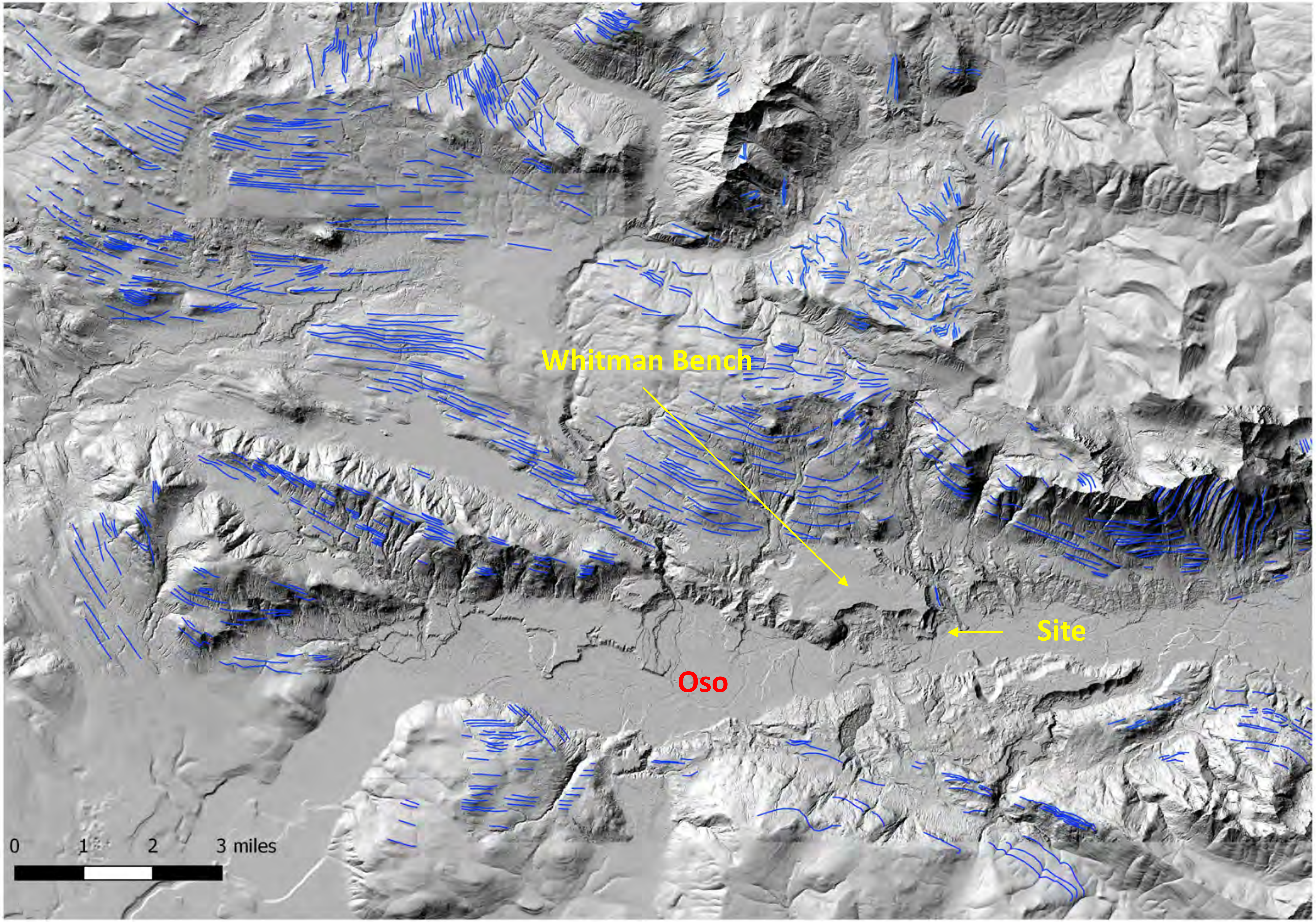
A Complicated BIG PICTURE (of Ice Flow Directions)

How do we know this???

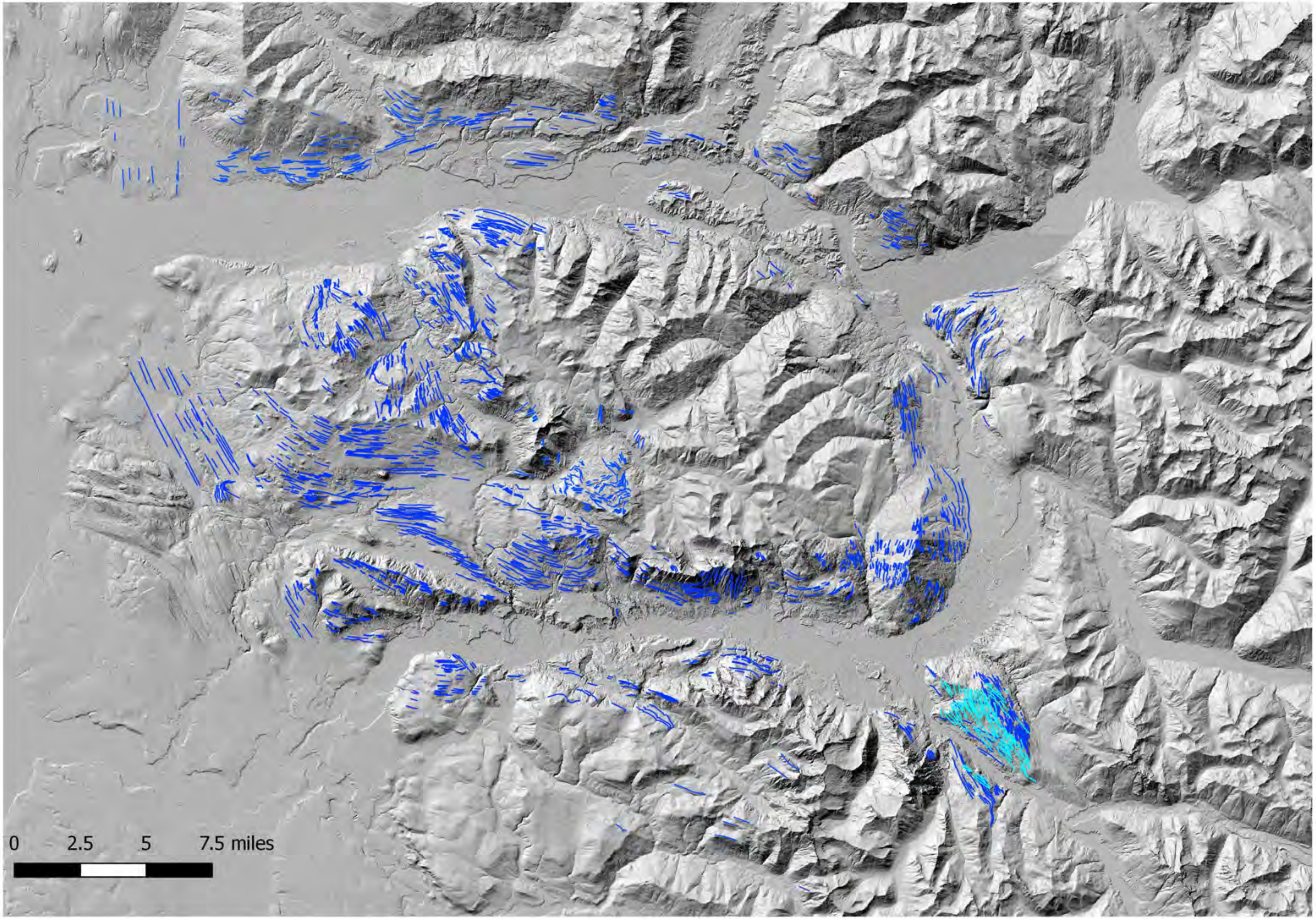


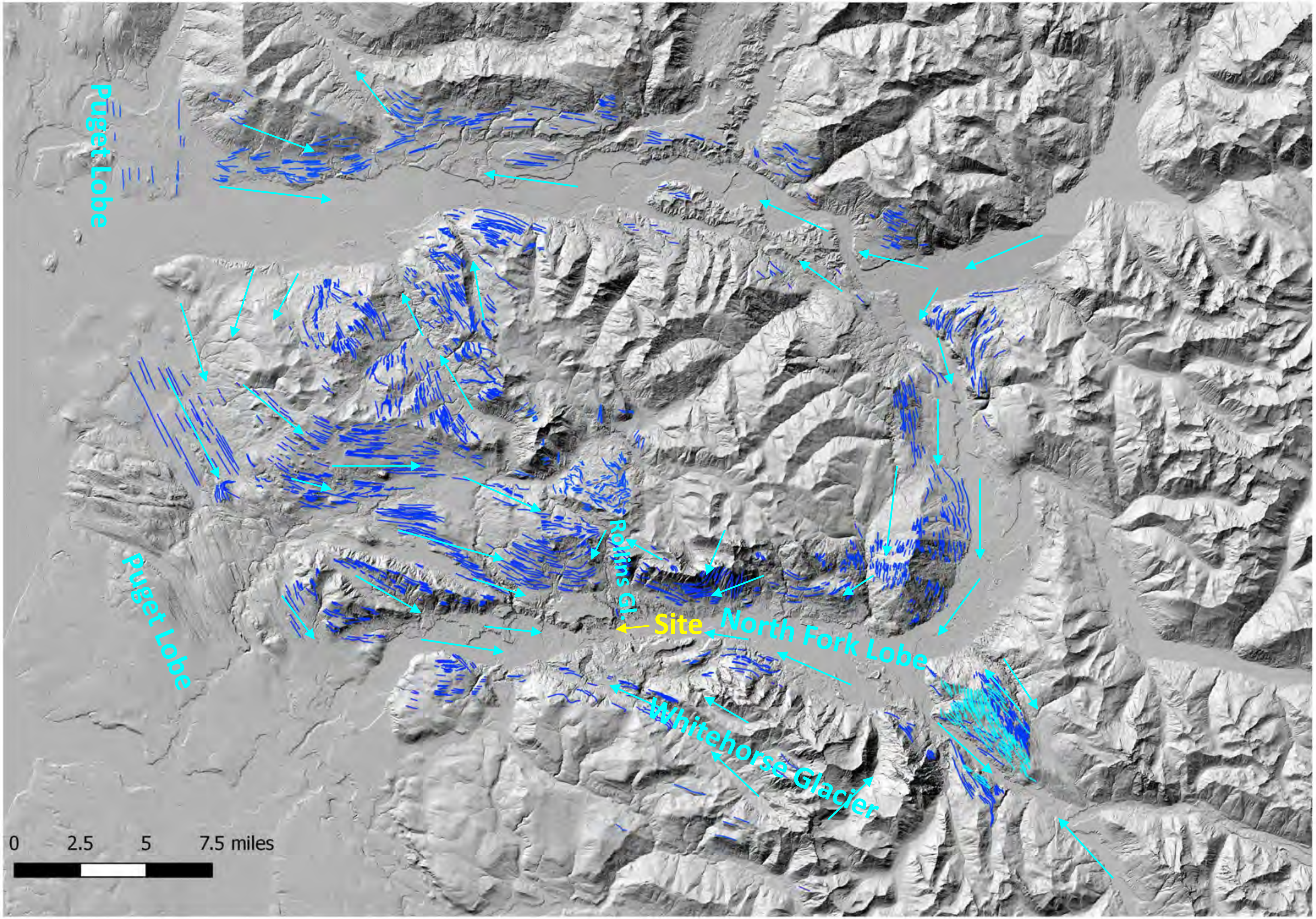

Ice Flow Cues
0 1000 2000 3000 ft


0 1000 2000 3000 ft

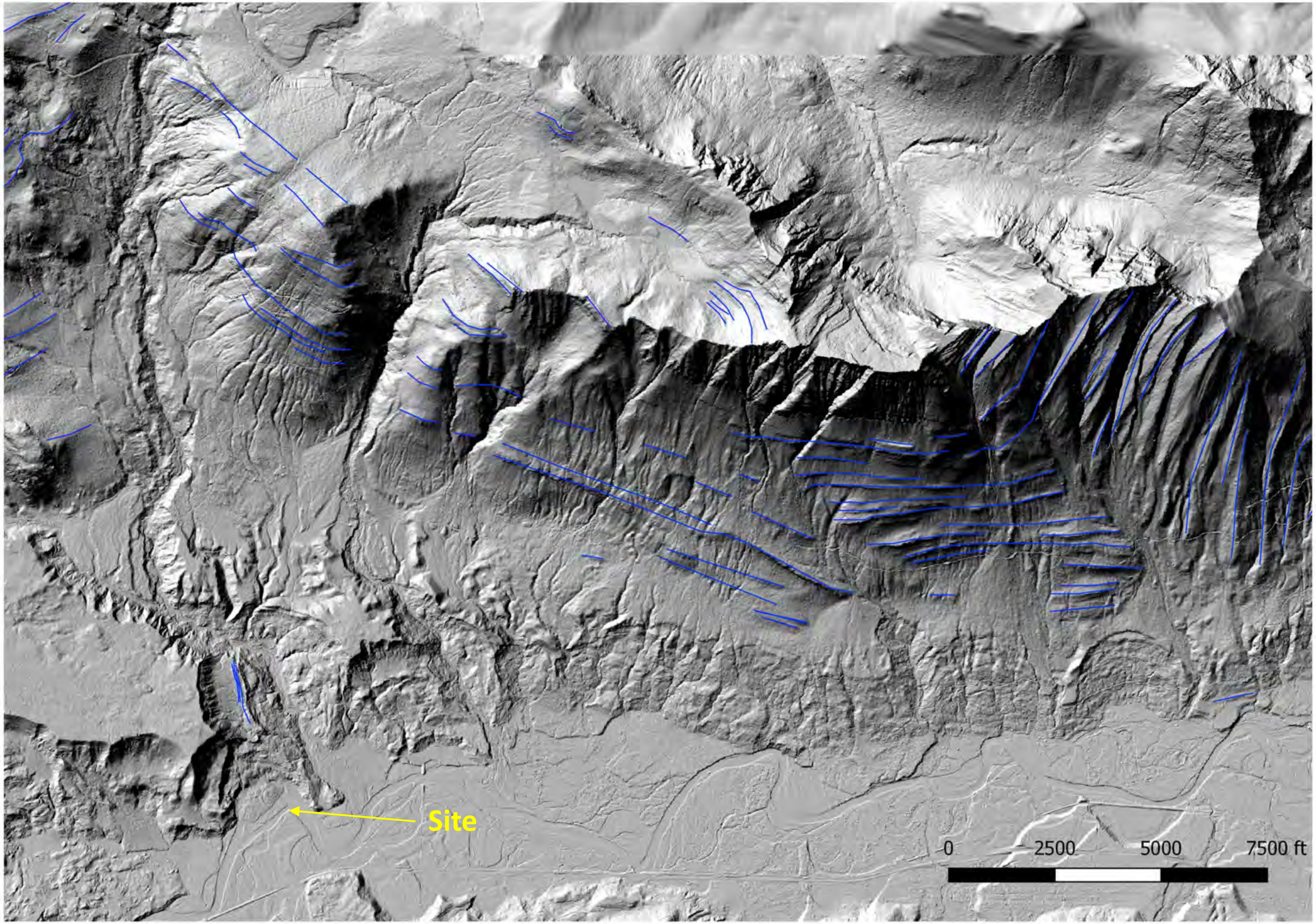


Whitman Bench
Site
Oso
0
1
2
3 miles


0 2.5 5 7.5 miles



Puget Lobe
Puget Lobe
Rollins Gl.
Site
North Fork Lobe
Whitehorse Glacier
0
2.5
5
7.5 miles


Site
0
2500
5000
7500 ft

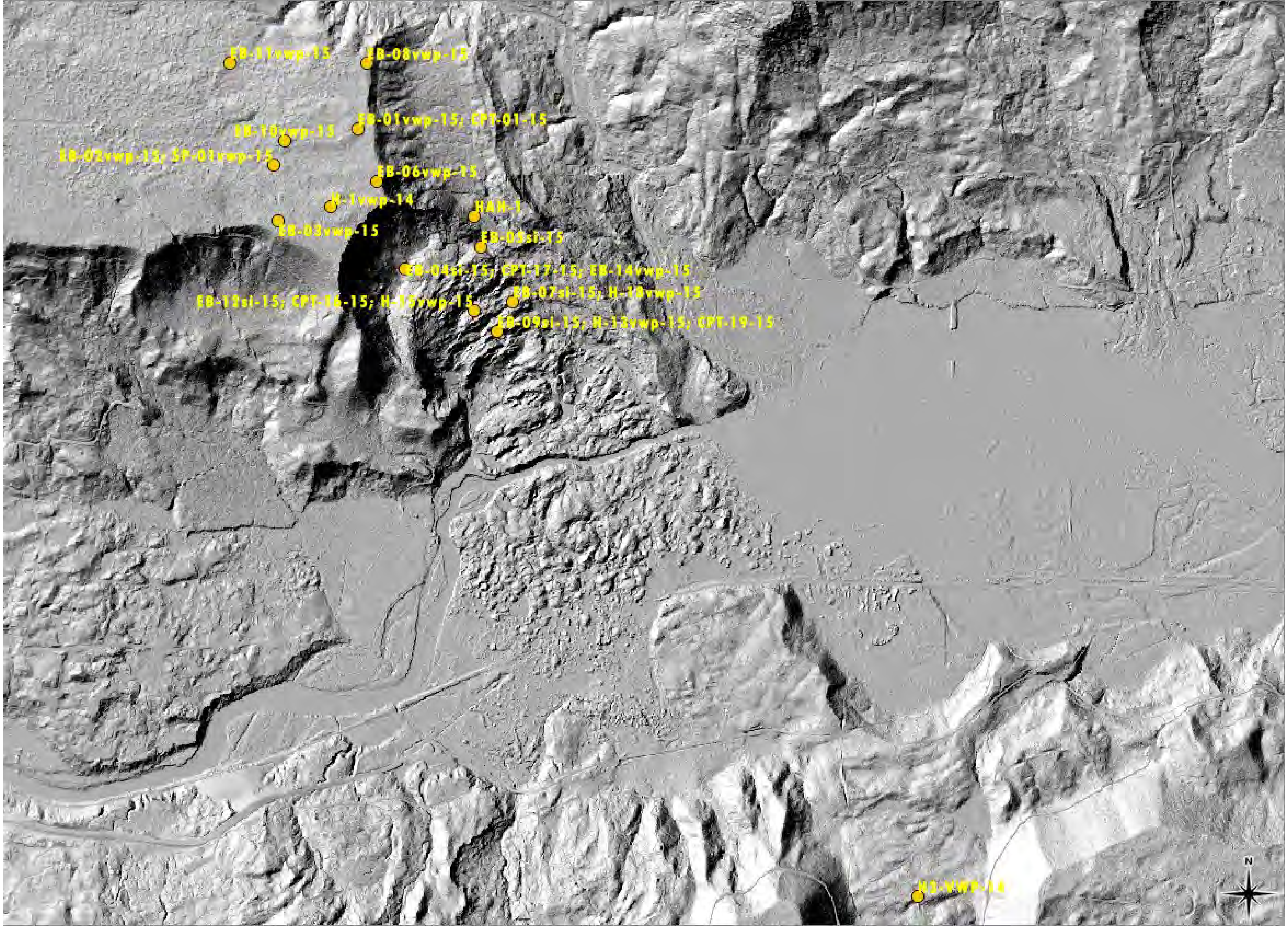
Whitman Bench is no Accident!

- Whitman Bench is located at this spot due to complex interaction of several different glaciers or glacial lobes.
- All glacial lobes were contributing sediment to this area
- Due to UNUSUAL converging ice flow directions, ice flow across the site was minor.
- This resulted in minimal glacial erosion, preserving significant portions of the uncemented sediments comprising the 600'-high benches.

Whitman Bench Stratigraphy (GEER, 7/22/14)

Overview of Slope Movement from SE
From GEER Report 7/22/14

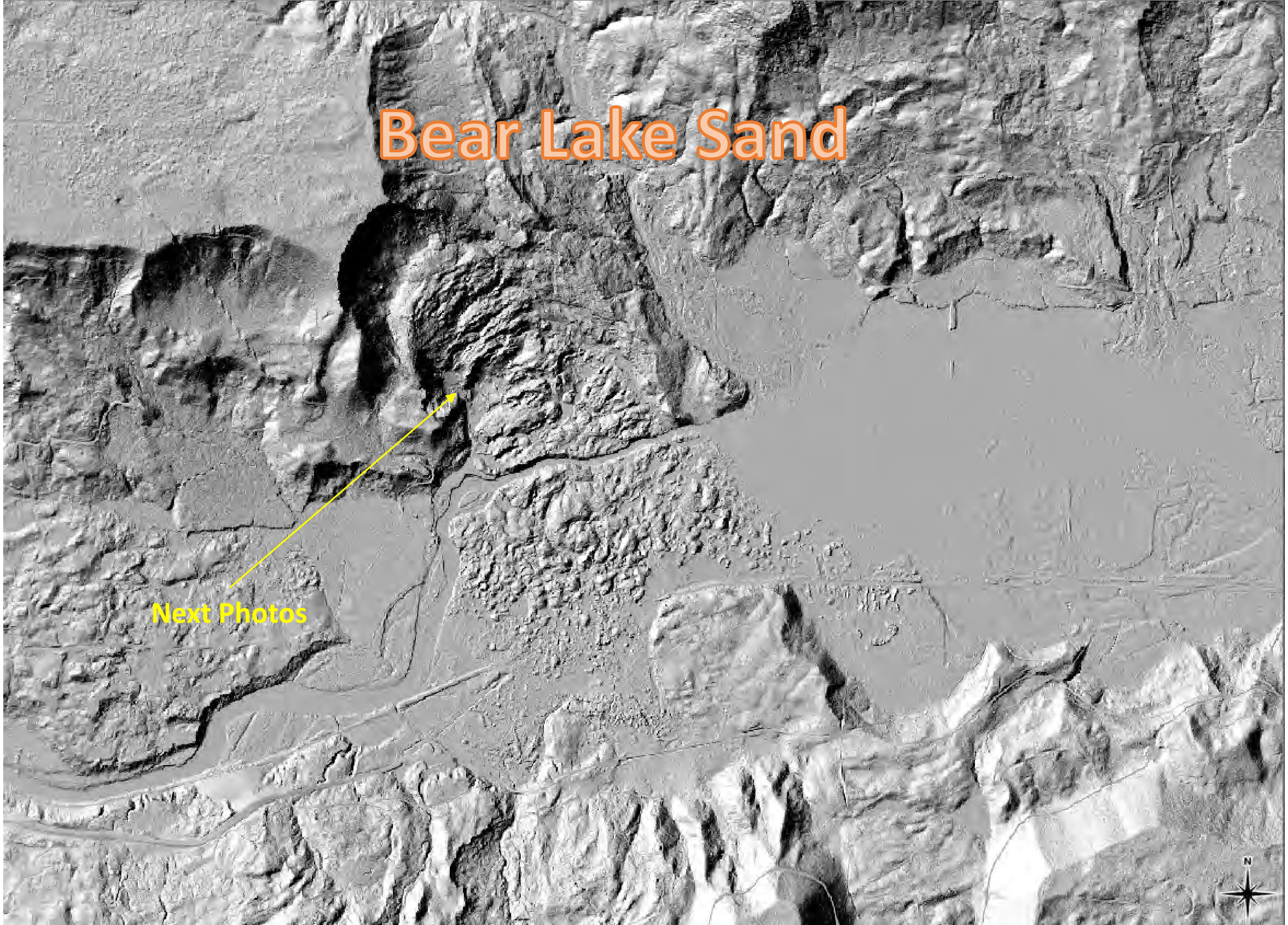
If only it were THAT SIMPLE!



EB-11vwp-15
EB-08vwp-15
EB-01vwp-15; CPT-01-15
EB-10vwp-15
EB-02vwp-15; SP-01vwp-15
EB-06vwp-15
H-1vwp-14
HAH-1
EB-03vwp-15
EB-05si-15
EB-04si-15; CPT-17-15; EB-14vwp-15
N

Whitman Bench Stratigraphy (Our Version)

UNIT	THICKNESS	UPPER CONTACT ELEV.
RECESSIONAL OUTWASH (deposited during deglaciation): Sand and Gravel (Includes Basal Silt)	67-134	Surface (832 – 892)
TILL COMPLEX: Discontinuous Lodgment Till Deformation Till Flow Till In some borings contains sections of stratified Silt, Sand, and Gravel	0 – 130’+	733.5 – 771’
ADVANCE OUTWASH (deposited prior to the ice covering the site) Mostly dark gray Silt/Silty Sand in thick Eastern Portion of Head-scarp Gravel Delta with Flow Tills in Central Portion of Head-scarp Ice-Contact Coarse Sand/Pebble Delta in West Portion of Head-scarp	7 – 188’	660 – 688’
BEAR LAKE RHYTHMITES Rhythmically Bedded (1/16” – ½”) Silt/Clay Couplets	75 – 300’+	400 – 653.5’
BEAR LAKE SAND Very fine- to Coarse-grained, Poorly Graded Sand Occasional Silt/Clay Rhythmite Interbeds	90+’	313 – 325’


Bear Lake Sand
Next Photos
N


Next Photo

Slide Deposit (Transported Recessional Outwash)
Failure Surface
Horizontal Top-set Beds
Fore-set Beds Dipping NW
Bear Lake Sand (Oldest Unit at the Site)


Transported Recessional Outwash
(Slide Deposit)
Failure Surface
Bear Lake Sand


Bear Lake Sand
Over-consolidated, Sheared Silt/Clay Rhythmite Interbed


Bear Lake Sand
P.18
Depth 134-135.5
Rec.
Ret.

Bear Lake Sand Summary:

- 90+ Feet of Poorly Graded Sand, Very Fine- to Coarse-Grained
- Foreset- and Topset-Bedded
- Occasional Silt/Clay Rhythmite Interbeds
- Occasional Drop Stones

- Origin: Deltaic Deposit in Lake

Moraine-Dammed Lake?

Problems:

1. NF Stillaguamish is a powerful river and would have eroded a moraine dam relatively fast.

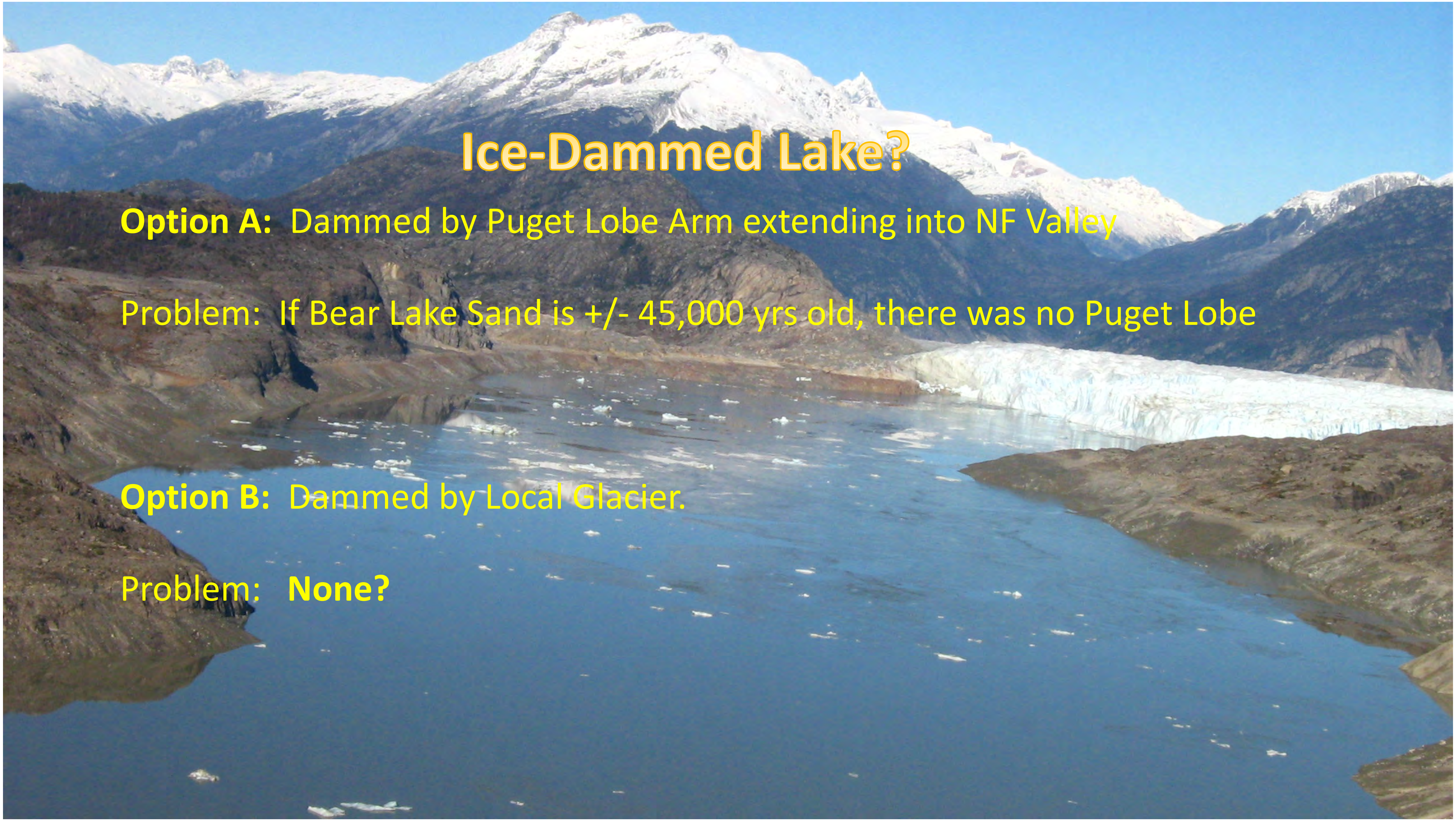
2. Silt/Clay Interbeds indicate fluctuating lake level during Bear Lake Sand time.

Landslide-Dammed Lake?

Problems:

1. NF Valley would have been +/- 3 miles wide.

2. Fluctuating lake level can’t be explained.



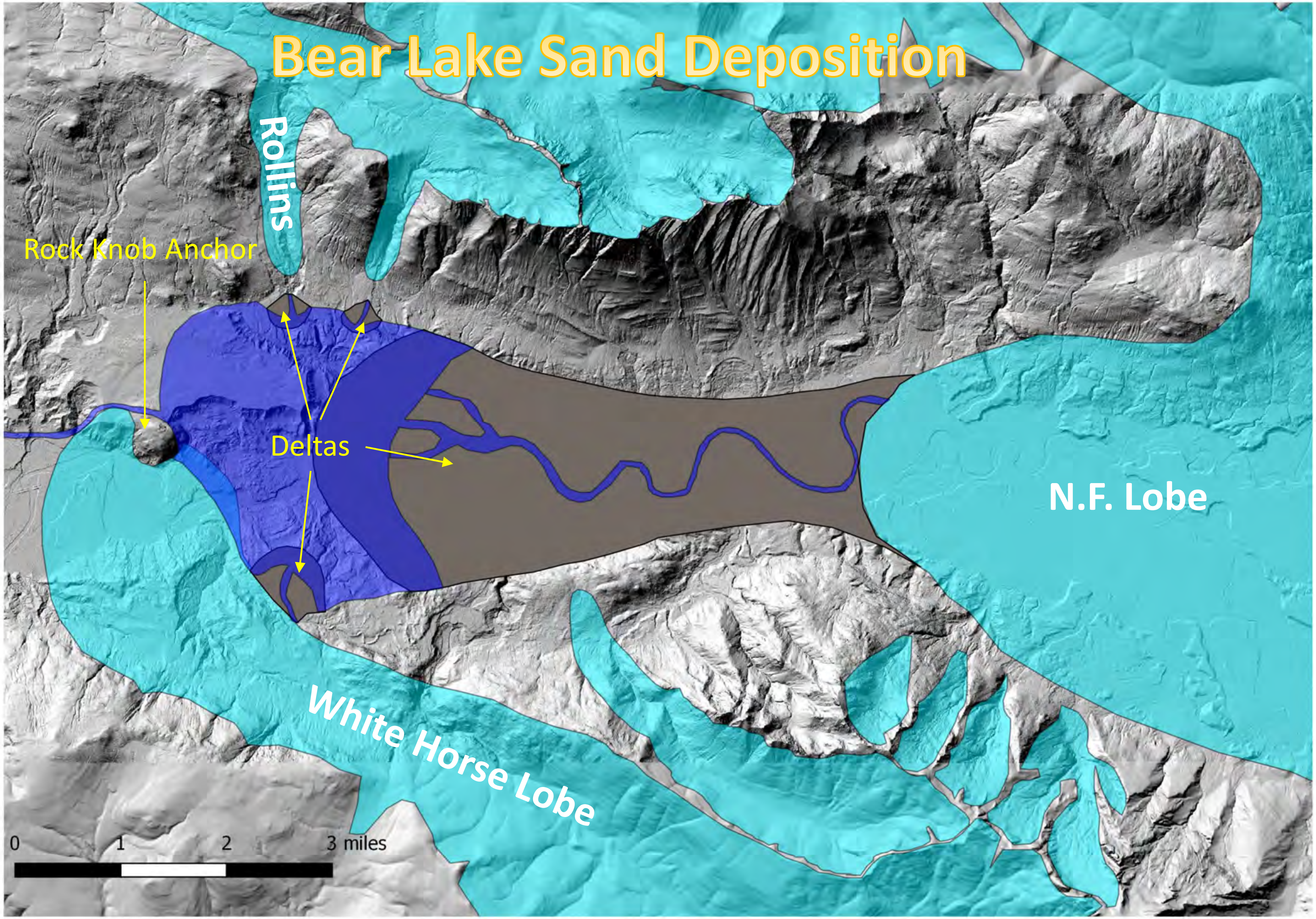
Ice-Dammed Lake?

Option A: Dammed by Puget Lobe Arm extending into NF Valley

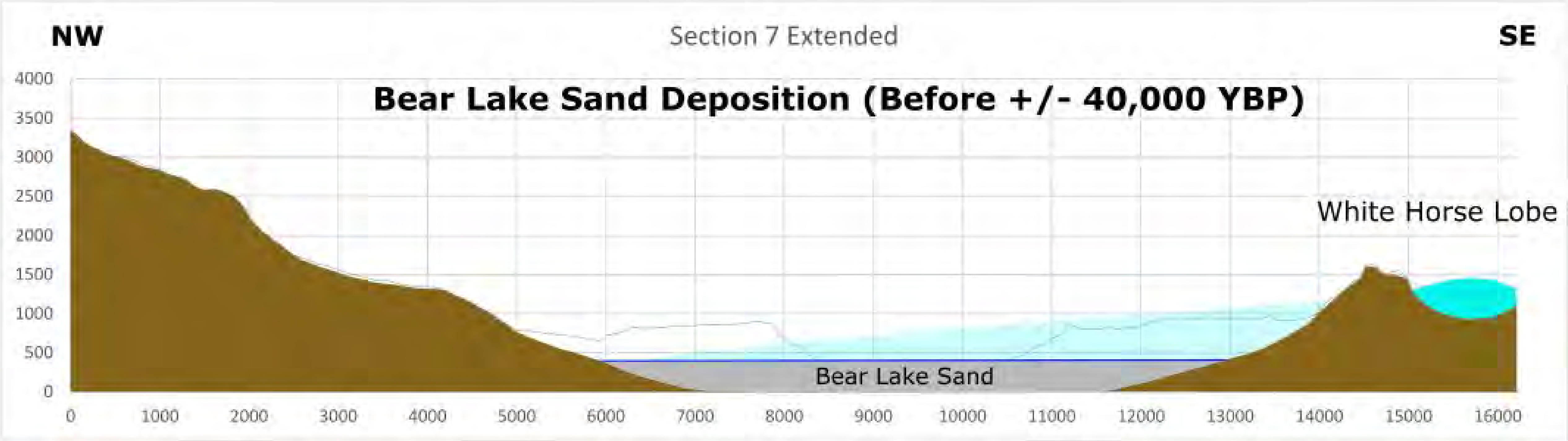
Problem: If Bear Lake Sand is +/- 45,000 yrs old, there was no Puget Lobe

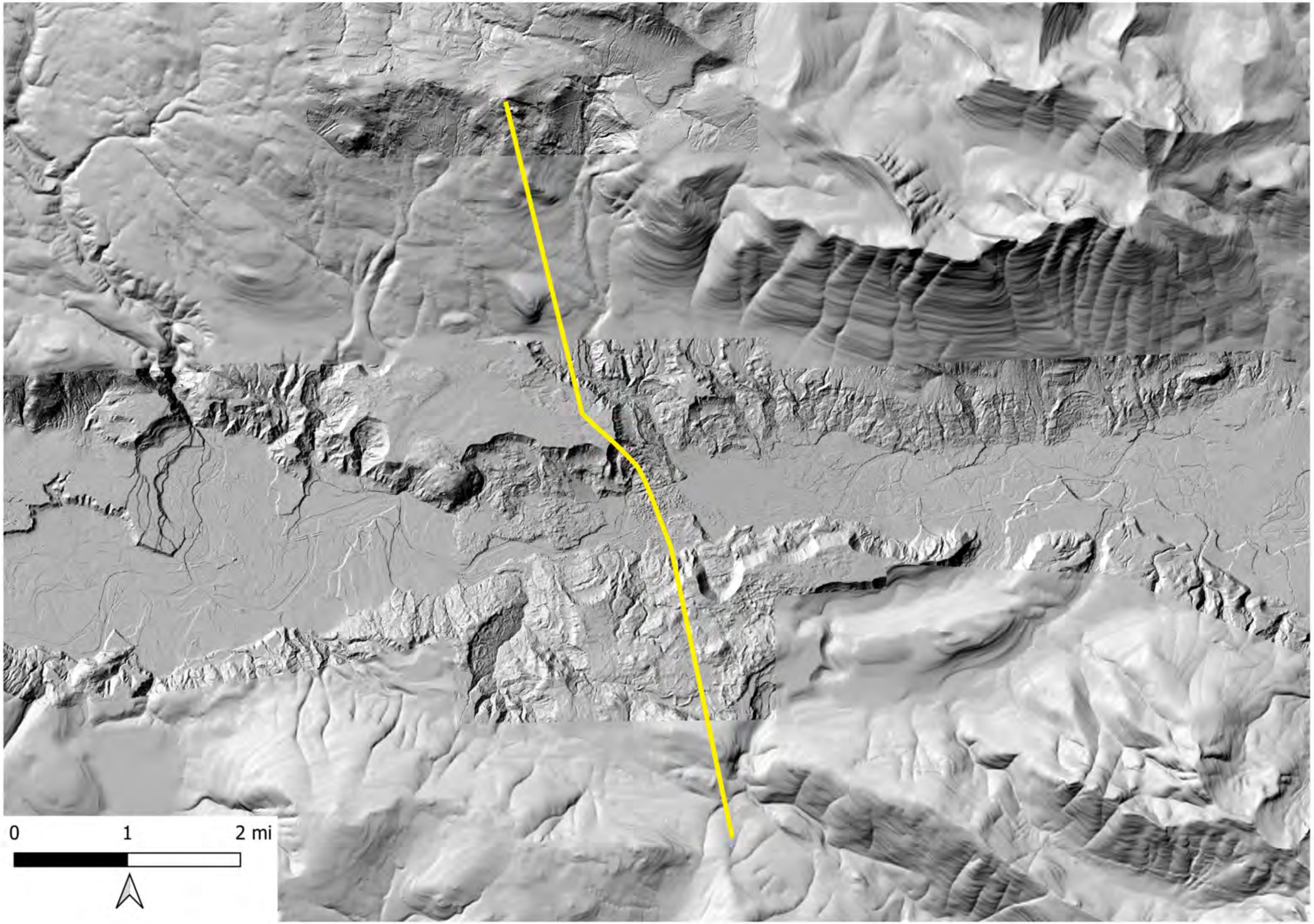
Option B: Dammed by Local Glacier.

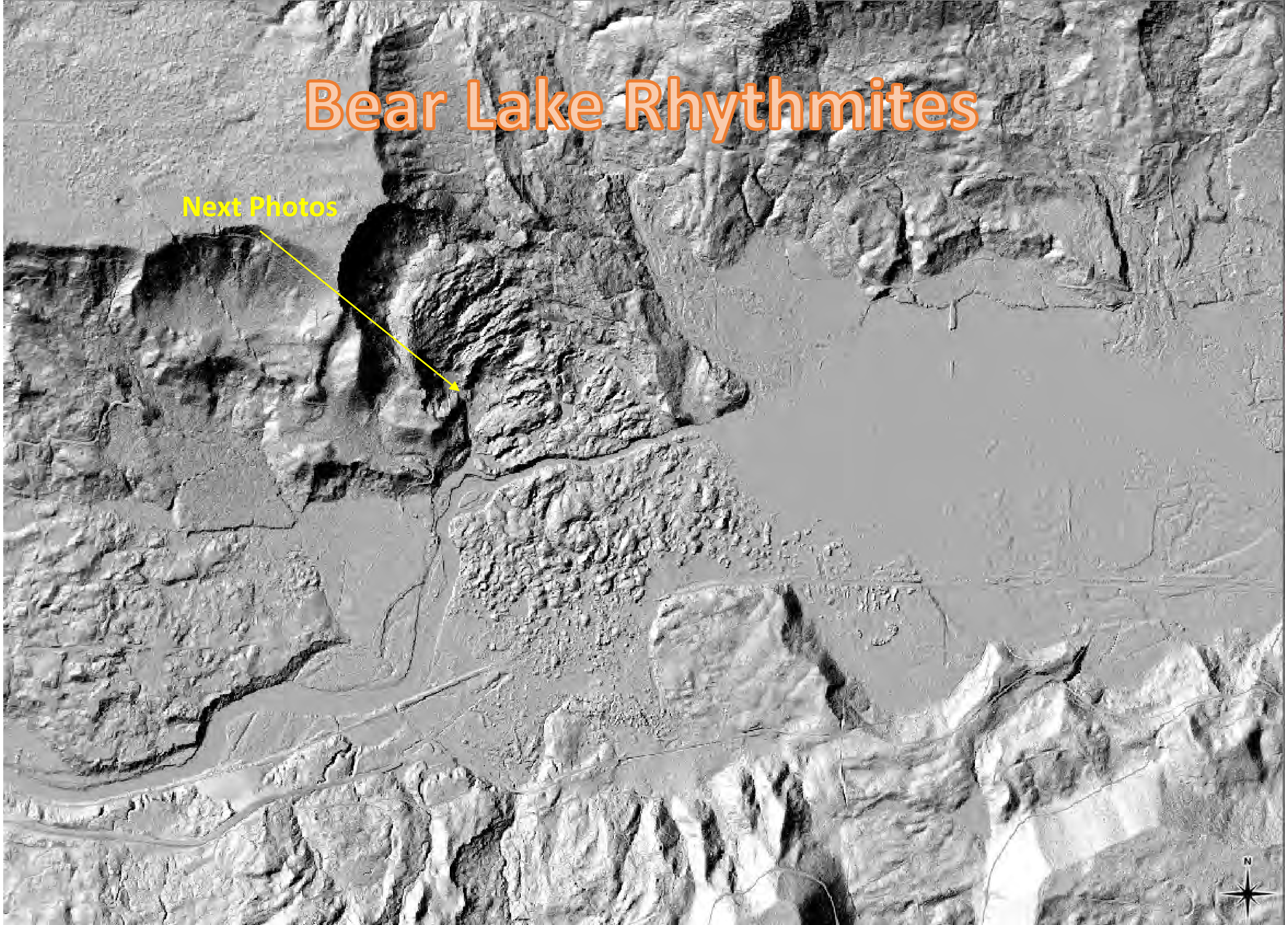
Problem: **None?**



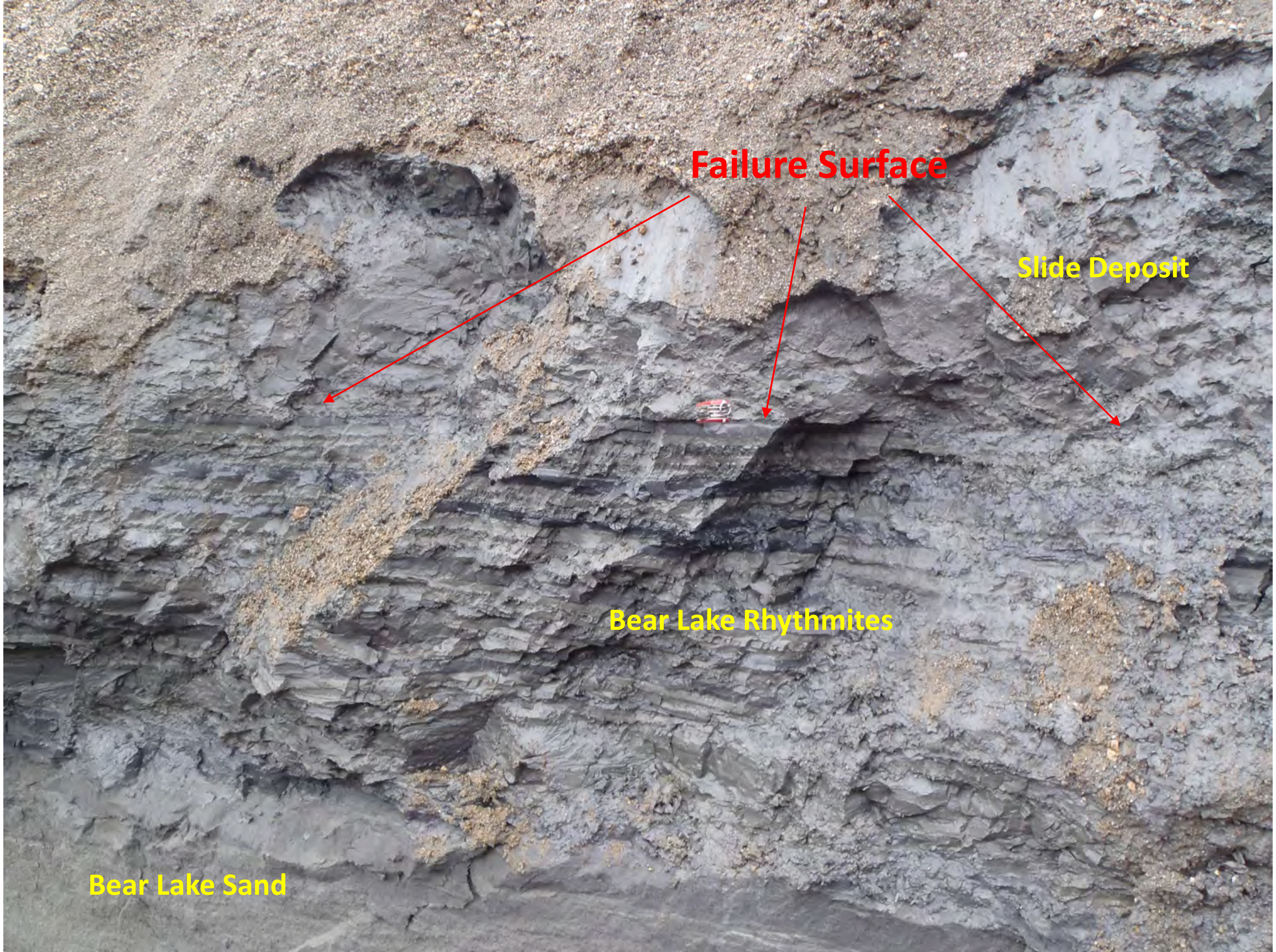
Bear Lake Sand Deposition
Rollins
Rock Knob Anchor
Deltas
N.F. Lobe
White Horse Lobe
0
1
2
3 miles

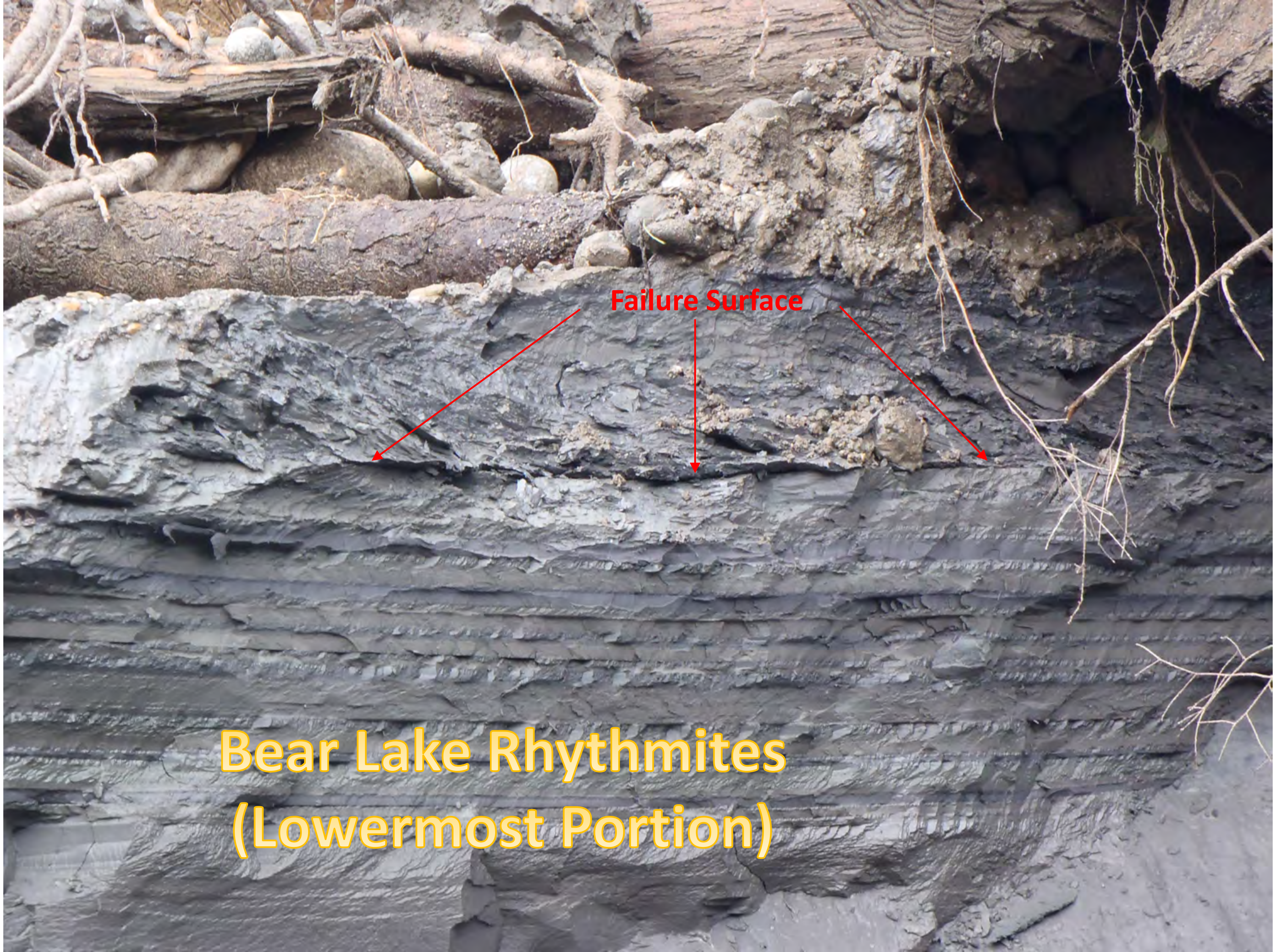

NW
Section 7 Extended
SE
Bear Lake Sand Deposition (Before +/- 40,000 YBP)
White Horse Lobe
Bear Lake Sand
4000
3500
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000


0
1
2 mi

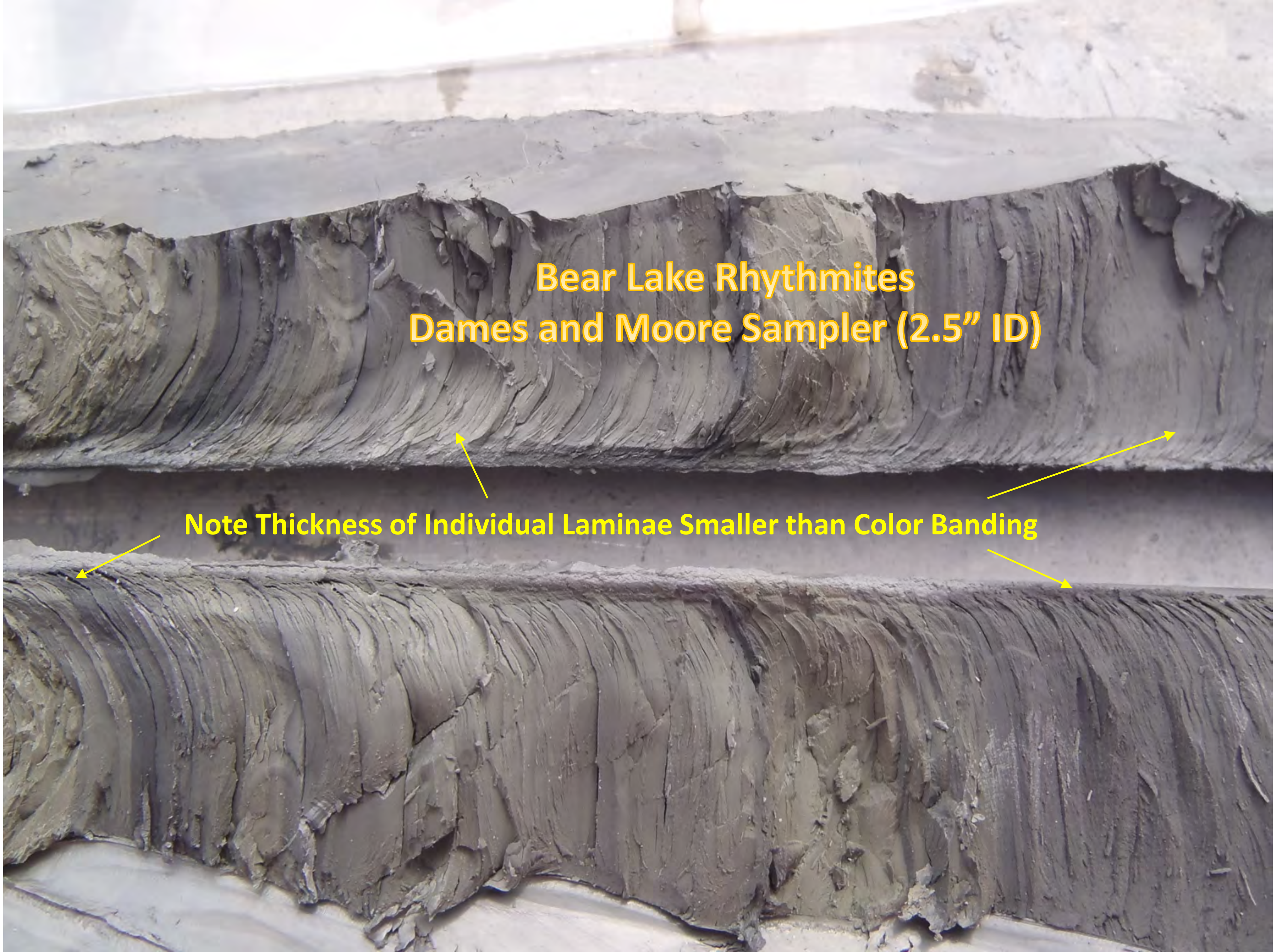

Bear Lake Rhythmites
Next Photos
N

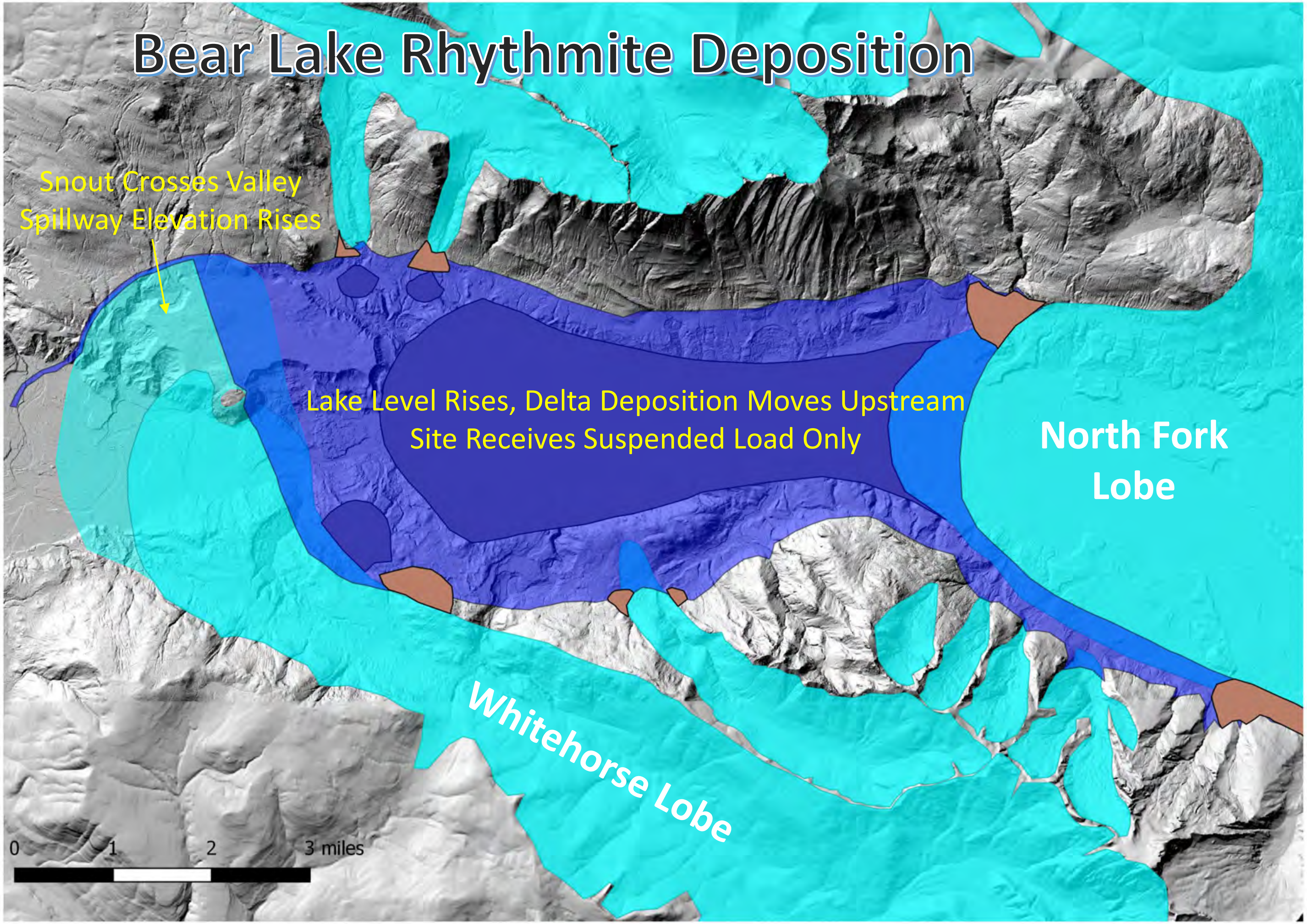

Slide Deposit
Bear Lake Rhythmites
Bear Lake Sand

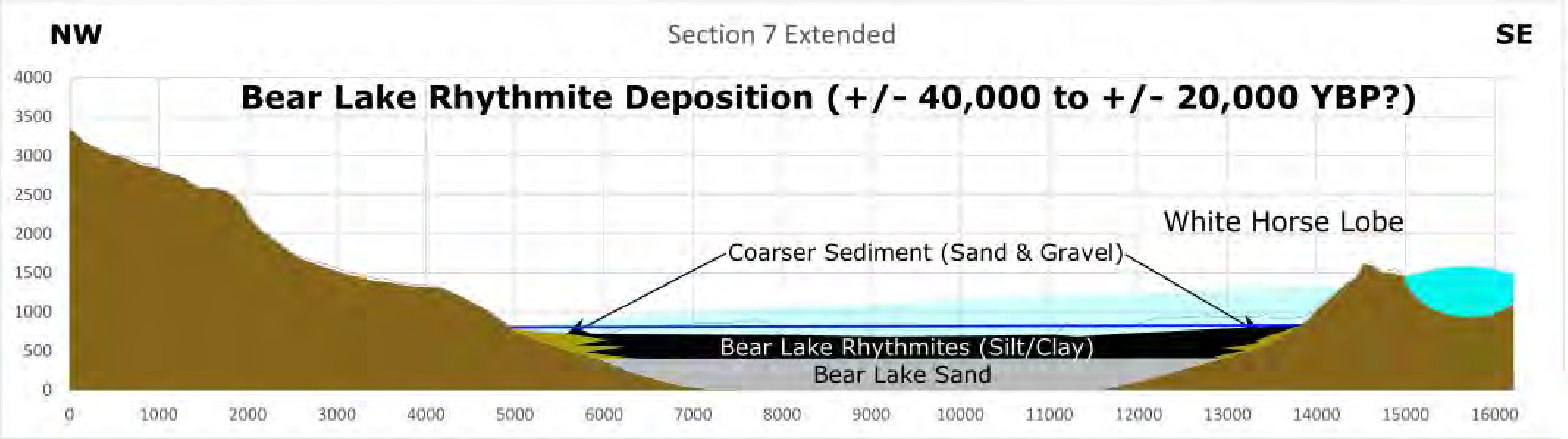

Failure Surface
Slide Deposit
Bear Lake Rhythmites
Bear Lake Sand


Failure Surface
Bear Lake Rhythmites
(Lowermost Portion)

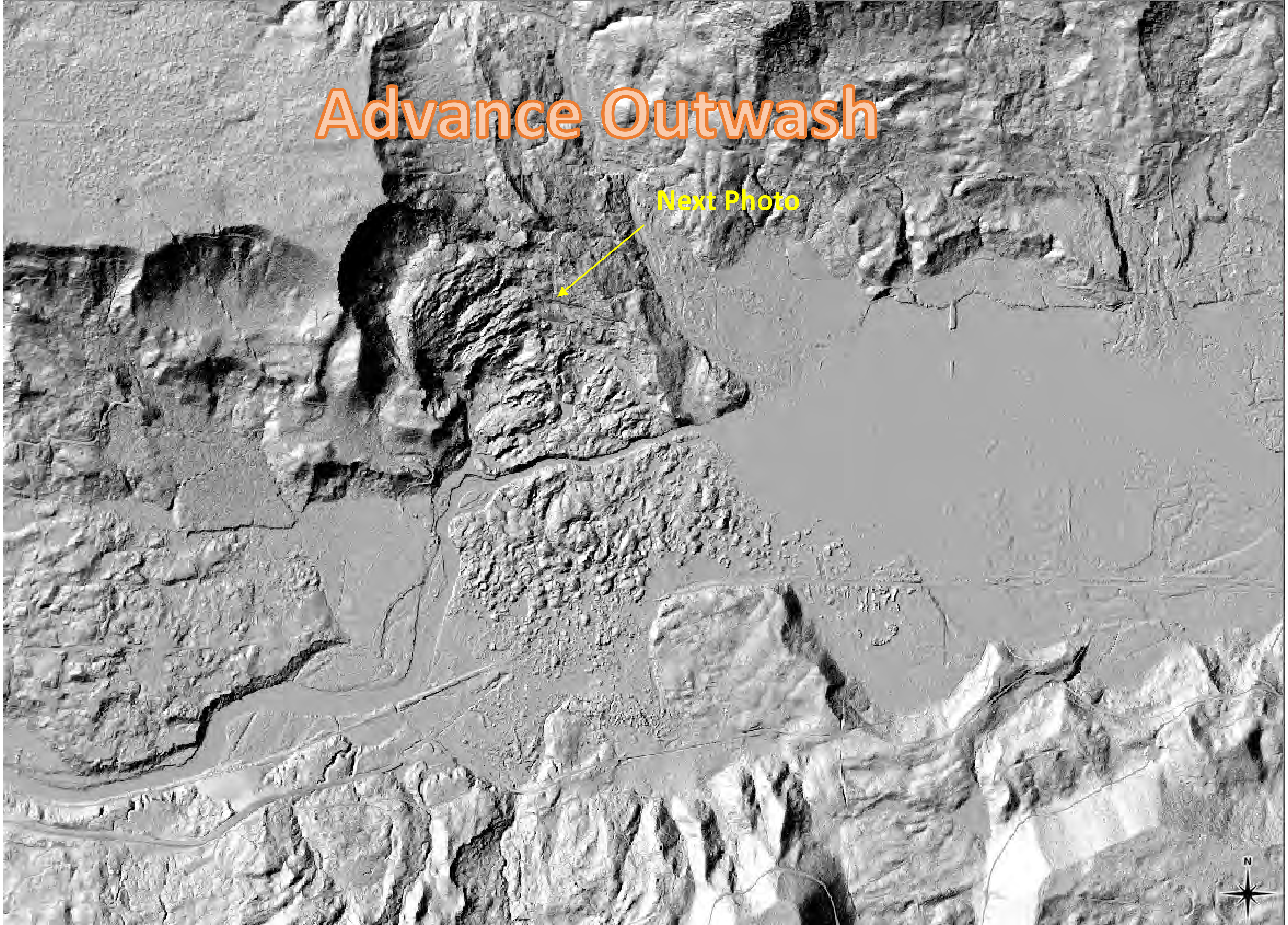
Bear Lake Rhythmites
Standard Penetration Test, EB-07, 78-80'
STANLEY
25ft


Bear Lake Rhythmites
Dames and Moore Sampler (2.5” ID)
Note Thickness of Individual Laminae Smaller than Color Banding

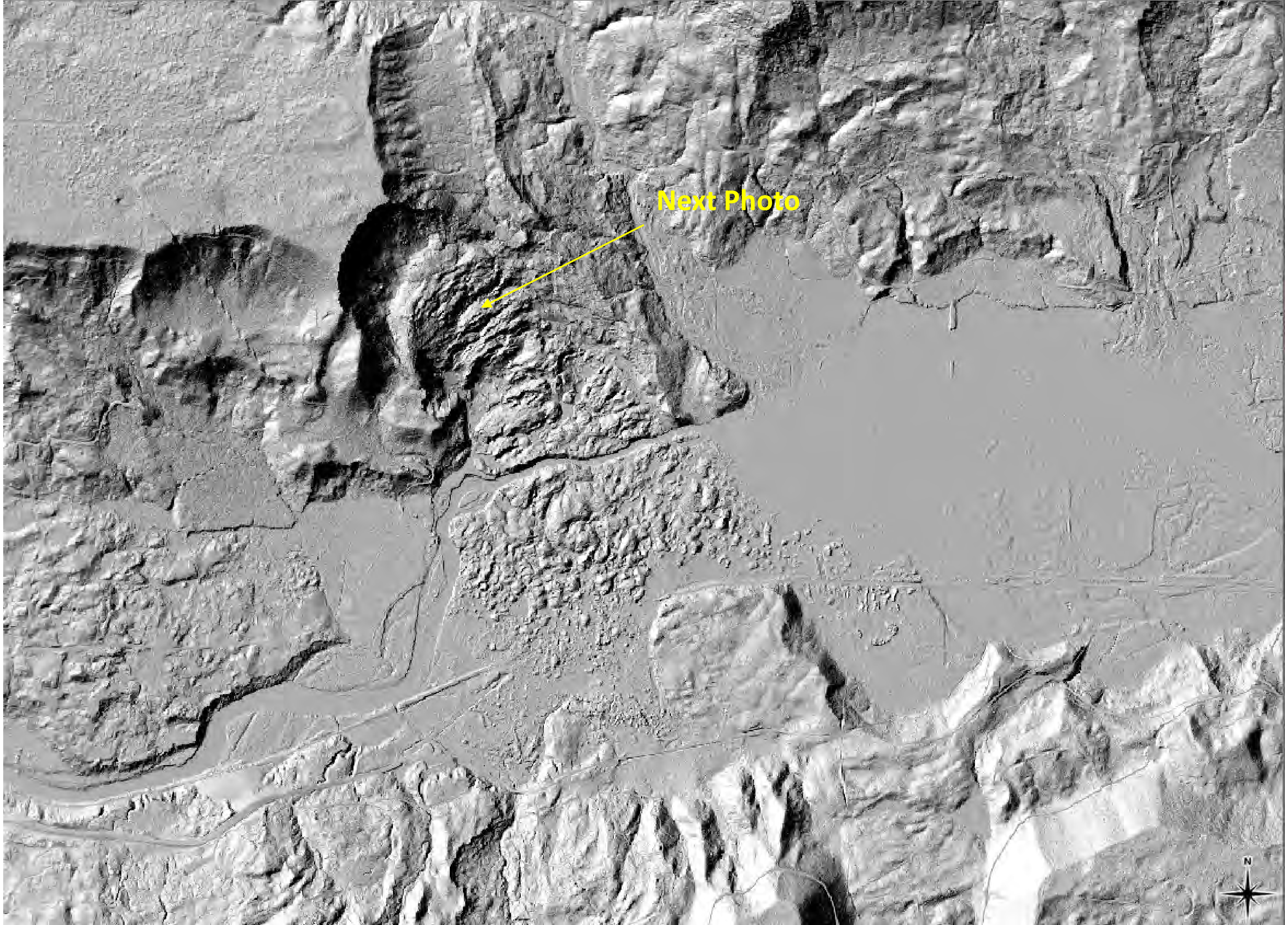

Bear Lake Rhythmite Deposition
Snout Crosses Valley
Spillway Elevation Rises
Lake Level Rises, Delta Deposition Moves Upstream
Site Receives Suspended Load Only
North Fork
Lobe
Whitehorse Lobe
0
1
2
3 miles

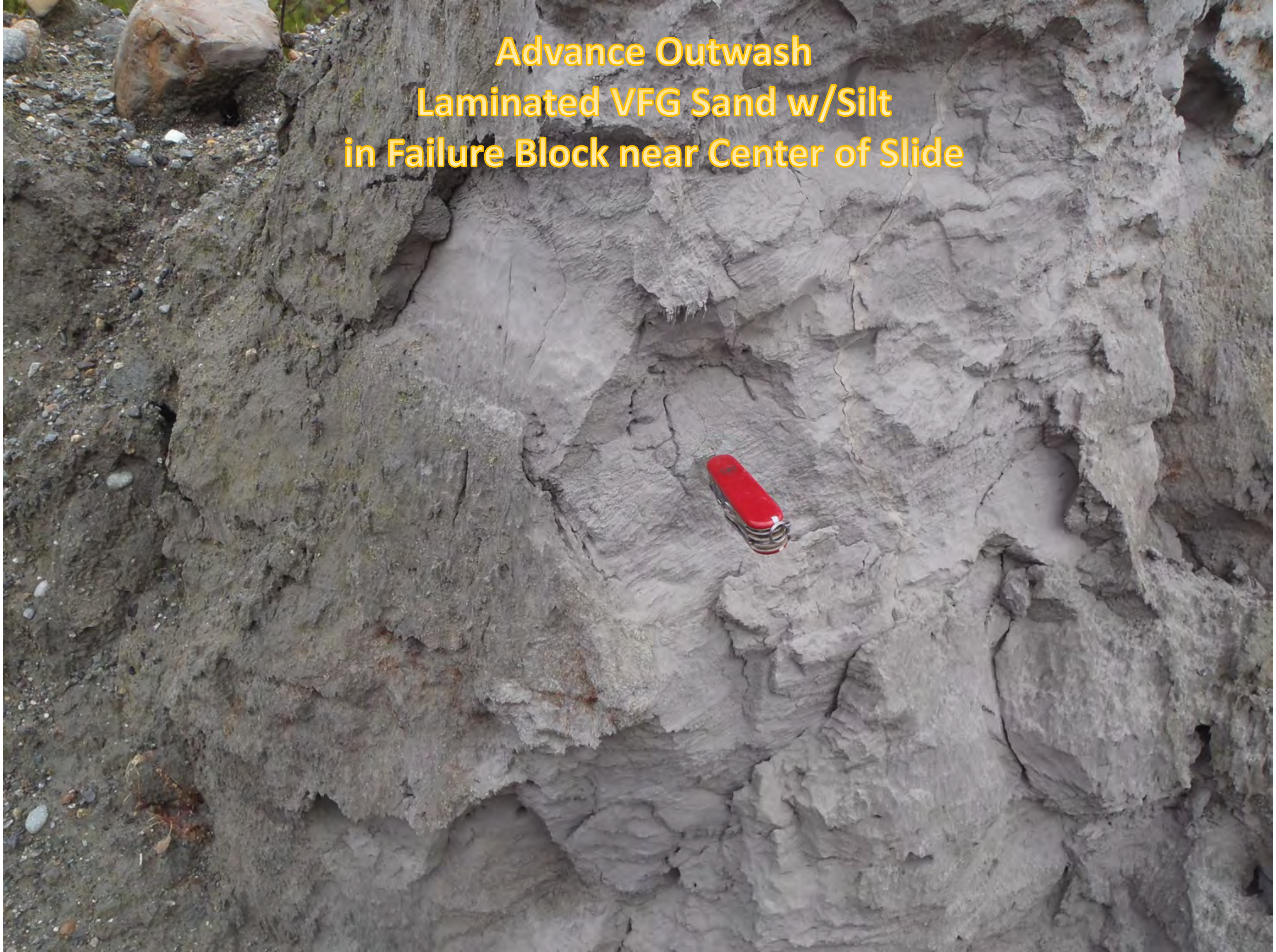

NW
Section 7 Extended
SE
Bear Lake Rhythmite Deposition (+/- 40,000 to +/- 20,000 YBP?)
White Horse Lobe
Coarser Sediment (Sand & Gravel)
Bear Lake Rhythmites (Silt/Clay)
Bear Lake Sand
4000
3500
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000

Advance Outwash




Advance Outwash Sandy Silt
Failing over BLR
East Margin, April 2016

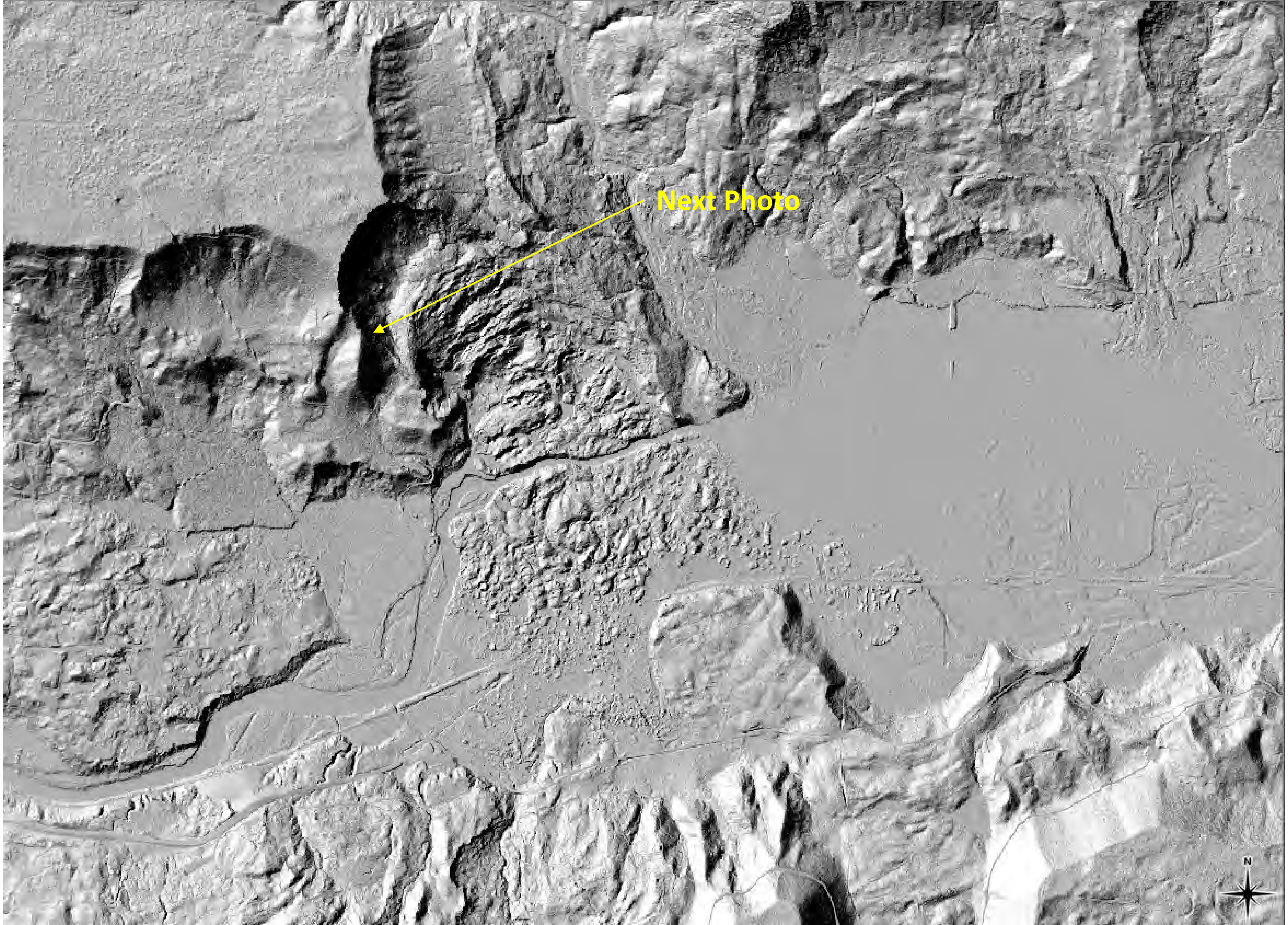

Next Photo
N

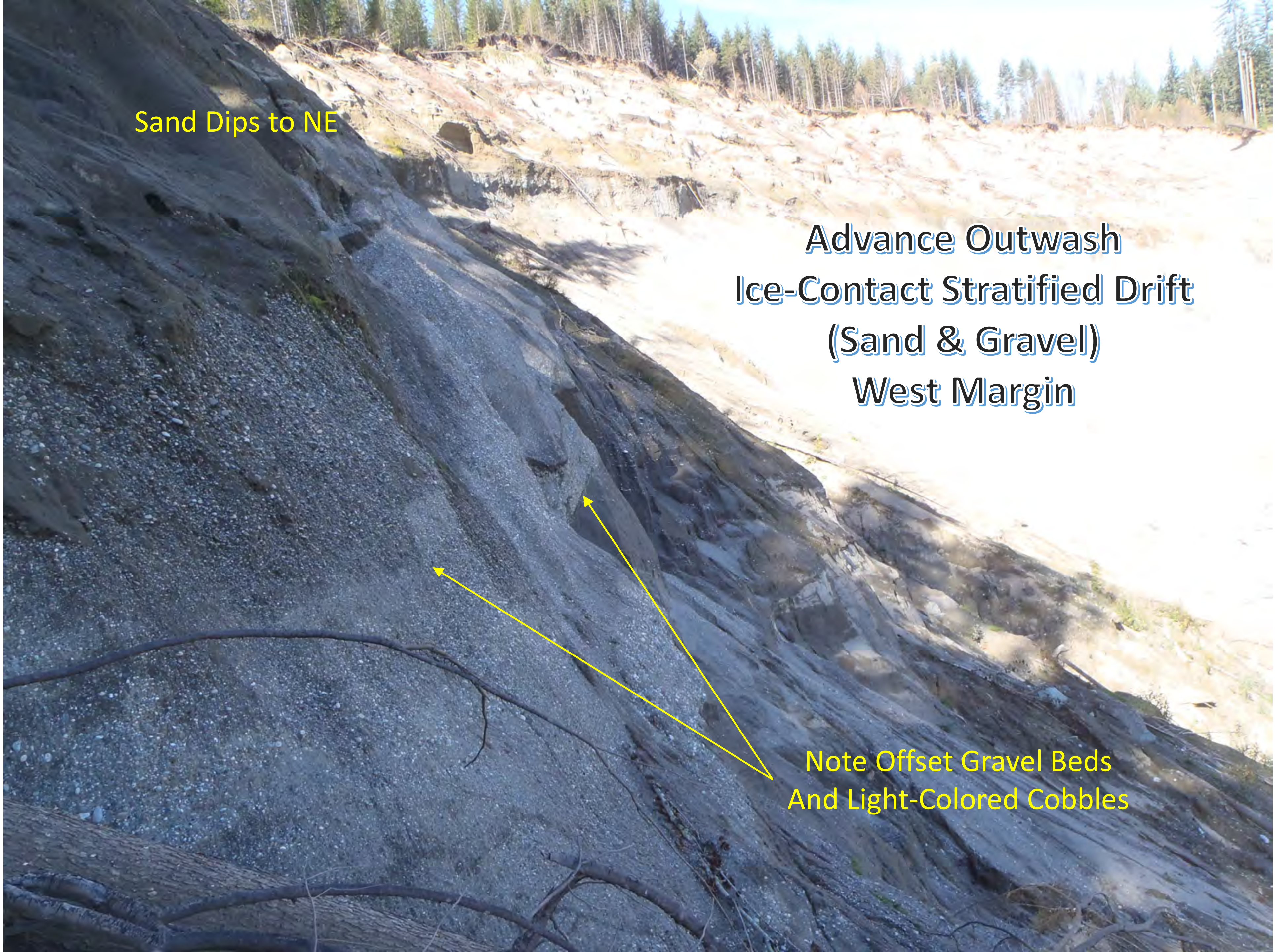

Advance Outwash
Laminated VFG Sand w/Silt
in Failure Block near Center of Slide


Advance Outwash
Laminated Sand


Advance Outwash
Center of Headscarp
+/-130' Recessional Outwash
Till
Till


Recessional Outwash
Till
Sand & Gravel
Advance Outwash
Central Head-scarp
Flow Till
Fore-set Beds Dip
Into Head-scarp (NW)

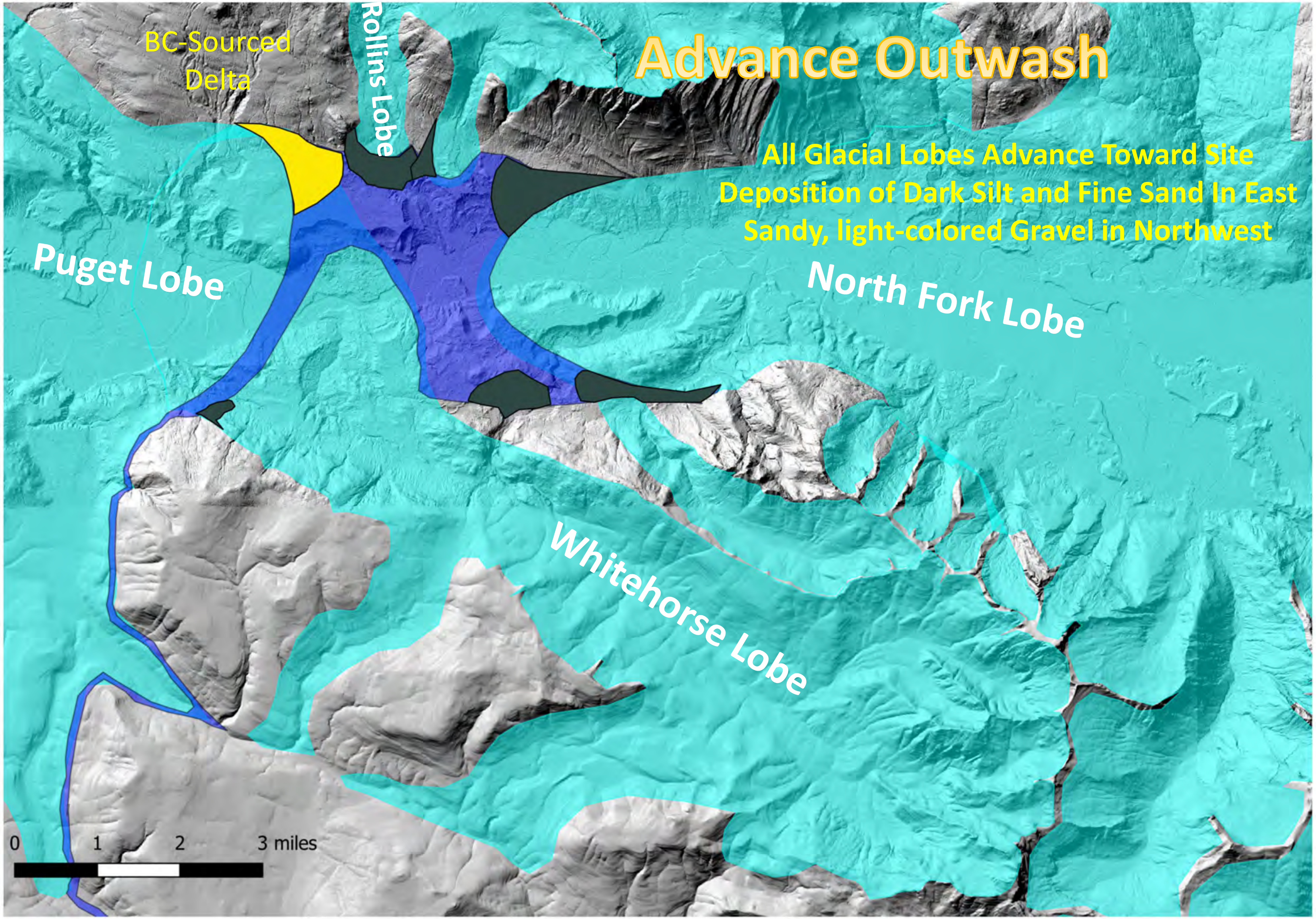

Next Photo
N


Sand Dips to NE
Advance Outwash
Ice-Contact Stratified Drift
(Sand & Gravel)
West Margin
Note Offset Gravel Beds
And Light-Colored Cobbles

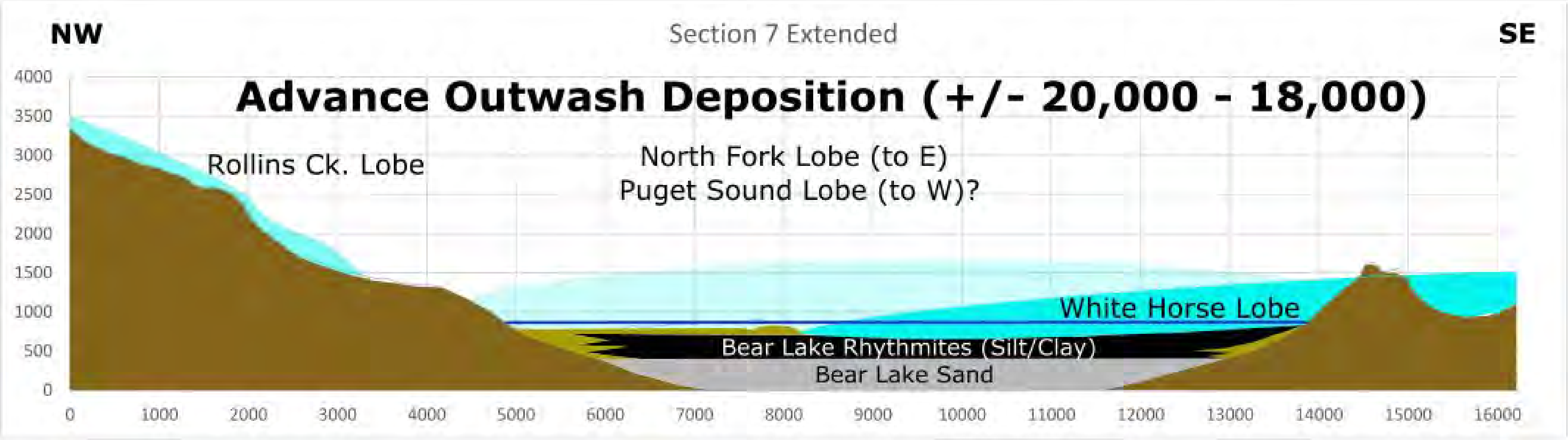
Advance Outwash Summary

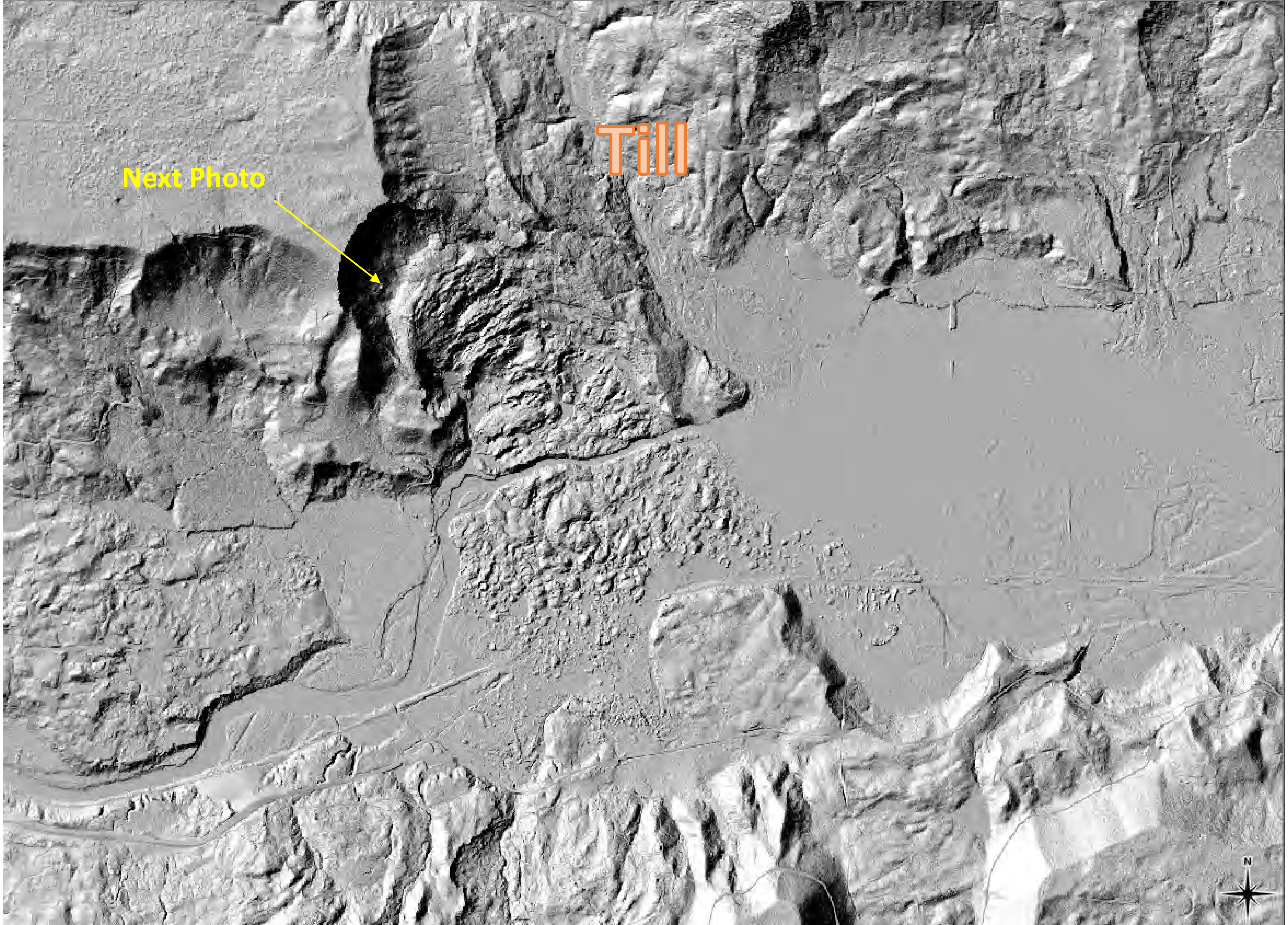
- Grainsize Highly Variable from Sandy Silt to Sandy Gravel
- Grainsize Location-dependent. Generally Finer-grained in East.
- Coarser Portions Fore-set Bedded.
- Portions Demonstrably Deposited in Contact with the Glacier.

- Deltaic and Lacustrine Origin

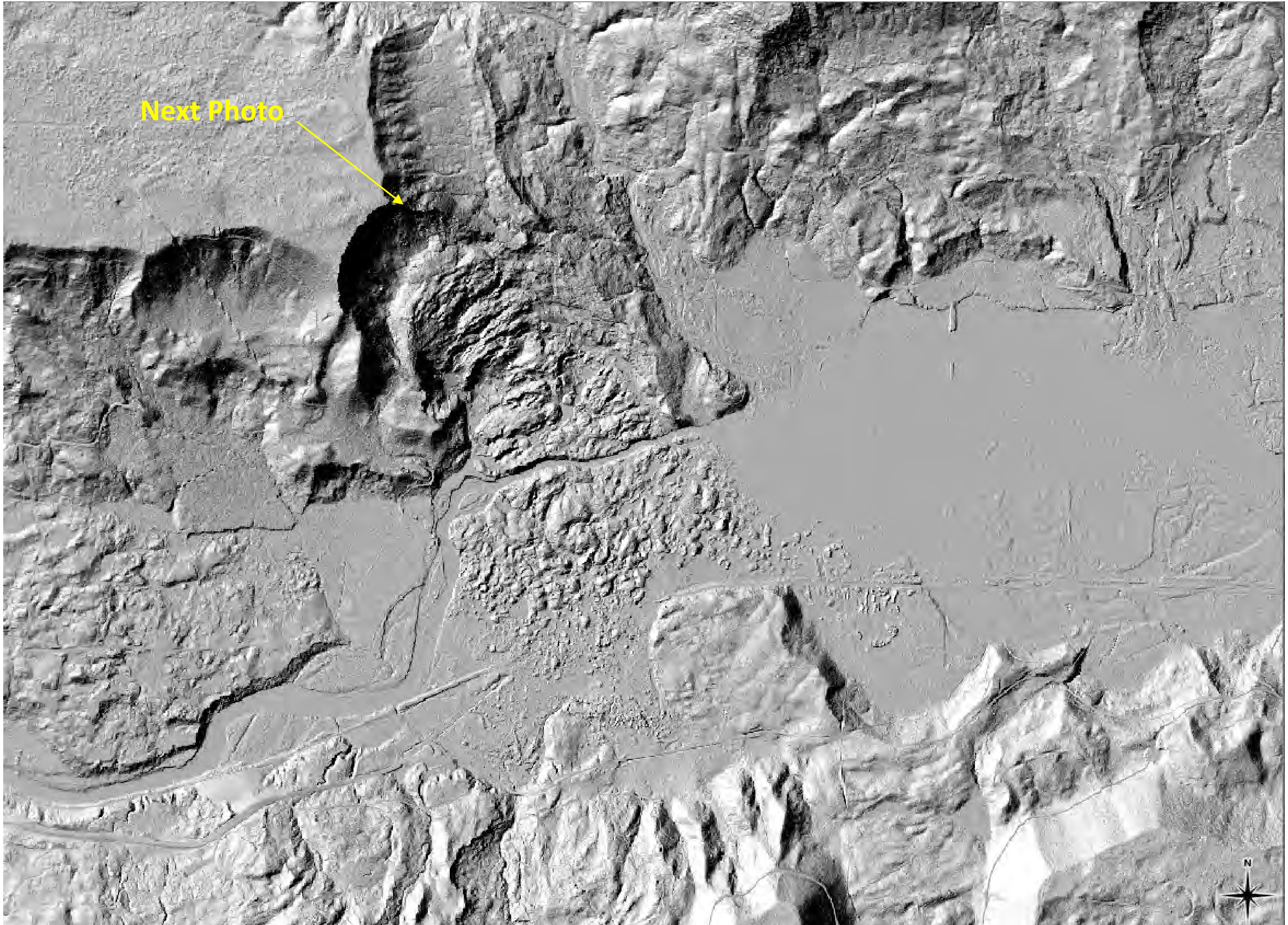


Advance Outwash
BC-Sourced Delta
Rollins Lobe
All Glacial Lobes Advance Toward Site
Deposition of Dark Silt and Fine Sand In East
Sandy, light-colored Gravel in Northwest
Puget Lobe
North Fork Lobe
Whitehorse Lobe
0 1 2 3 miles

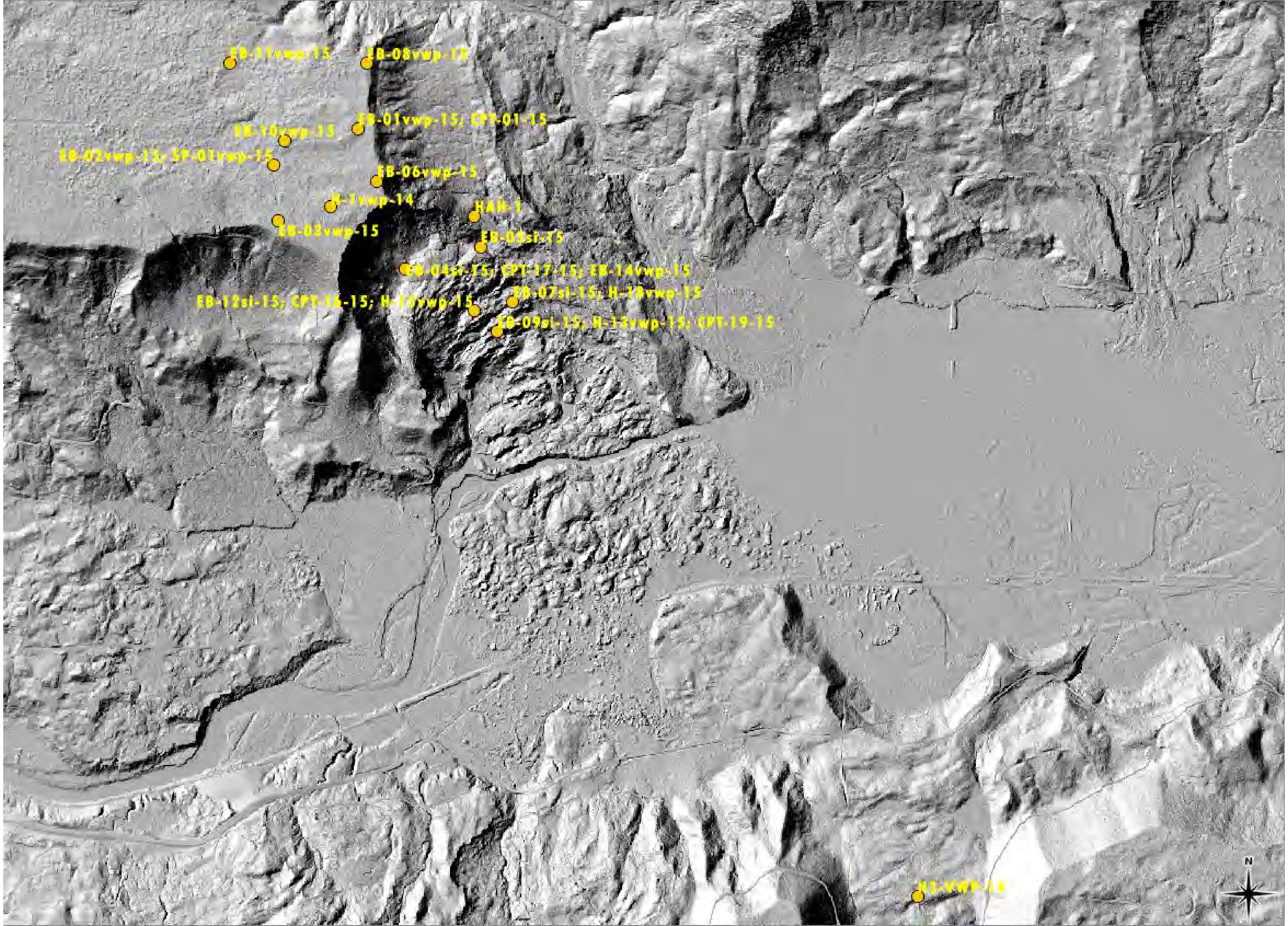

NW
Section 7 Extended
SE
Advance Outwash Deposition (+/- 20,000 - 18,000)
Rollins Ck. Lobe
North Fork Lobe (to E)
Puget Sound Lobe (to W)?
White Horse Lobe
Bear Lake Rhythmites (Silt/Clay)
Bear Lake Sand
4000
3500
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000


Till
Next Photo
N

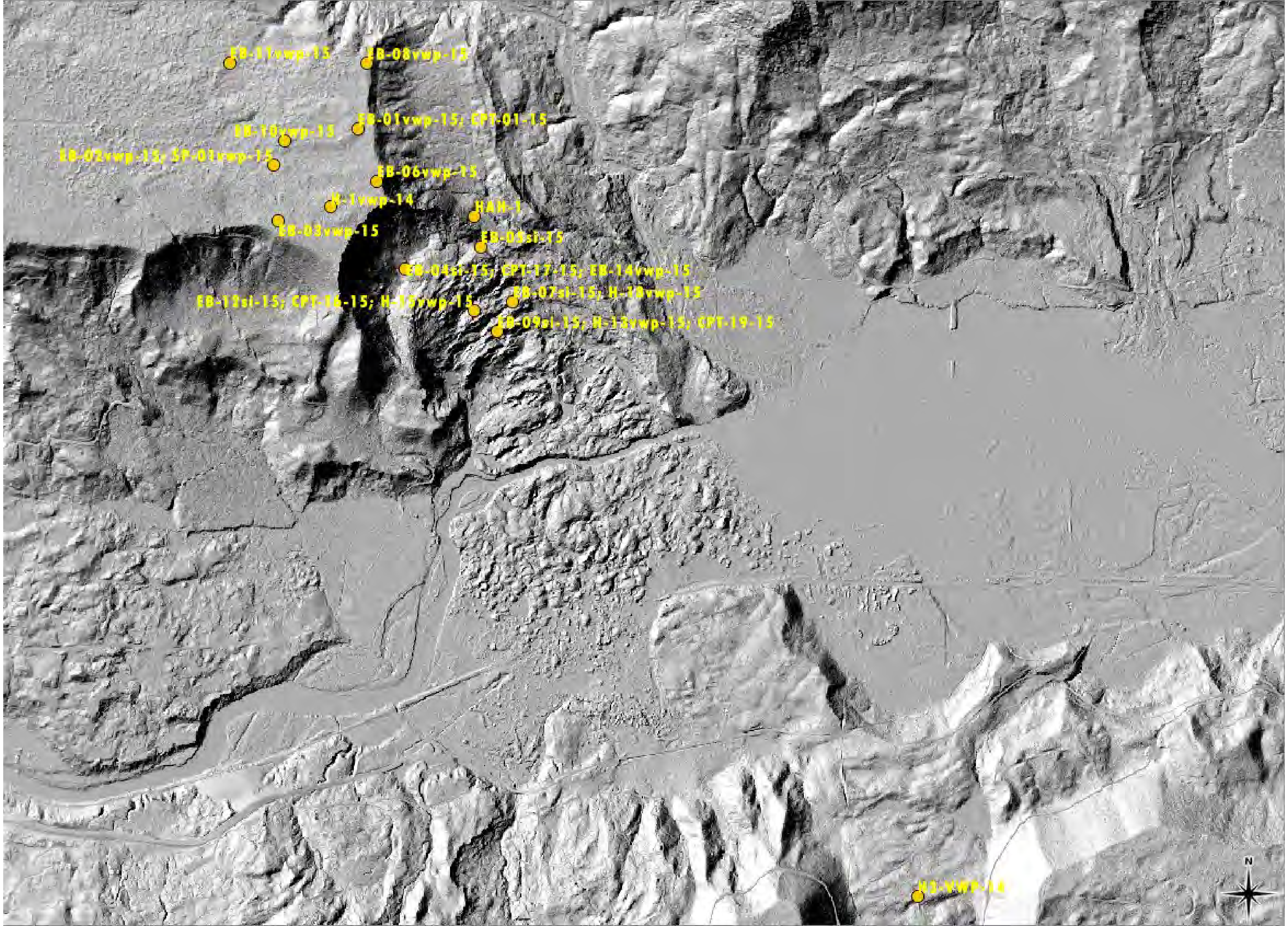
Lodgment Till Block in
Talus Beneath Head-scarp
Note Subdued Darker Cobble/Boulder Colors


Next Photo
N


Skadulgwas Peak
Lodgment and Flow Till in Eastern Headscarp
(100'+)
Head-scarp Collapse
Till Blocks
CME 850 & Excavator

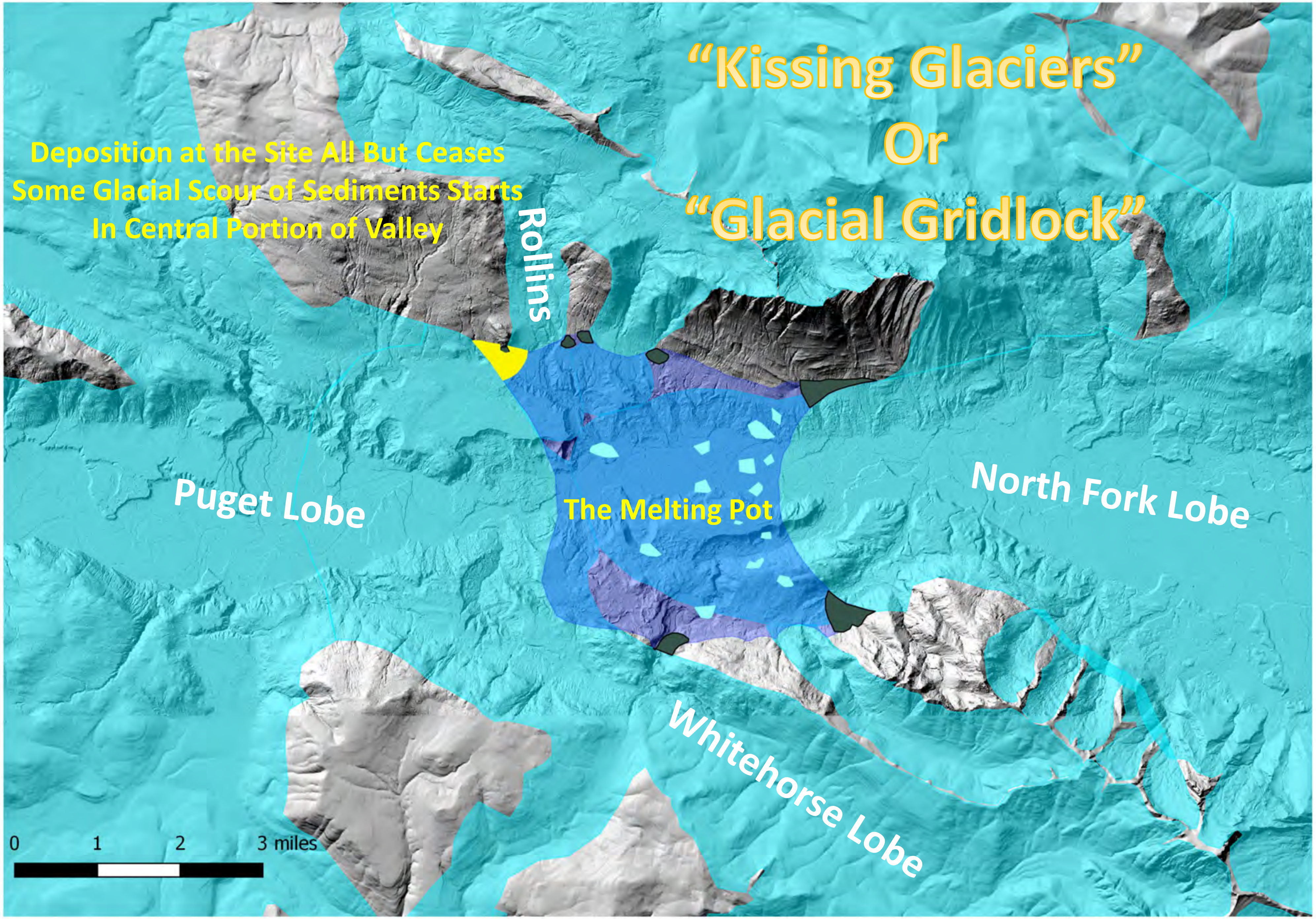

EB-11vwp-15
EB-08vwp-15
EB-01vwp-15; CPT-01-15
EB-10vwp-15
EB-02vwp-15; SP-01vwp-15
EB-06vwp-15
H-1vwp-14
HAH-1
EB-03vwp-15
EB-05si-15
EB-04si-15; CPT-17-15; EB-14vwp-15
EB-12si-15; CPT-16-15; H-15vwp-15
EB-07si-15; H-18vwp-15
EB-09si-15; H-13vwp-15; CPT-19-15
H3-VWP-14
N

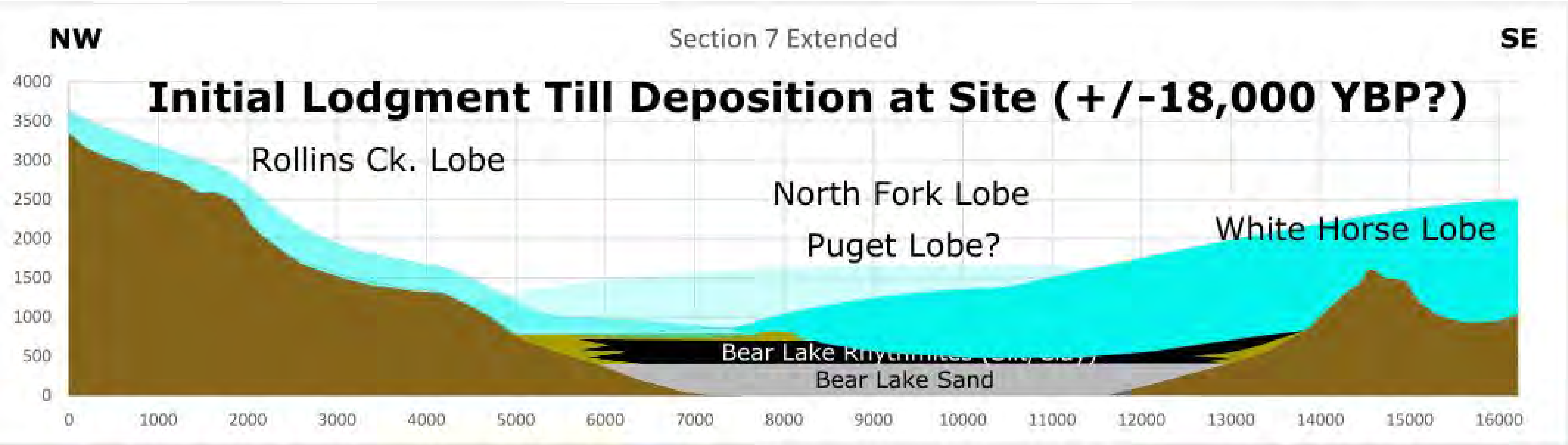

Lodgment Till Core in EB-02
C-15
122'


EB-11vwp-15
EB-08vwp-15
EB-01vwp-15; CPT-01-15
EB-10vwp-15
EB-02vwp-15; SP-01vwp-15
EB-06vwp-15
H-1vwp-14
HAH-1
EB-03vwp-15
EB-05si-15
EB-04si-15; CPT-17-15; EB-14vwp-15
EB-07si-15; H-18vwp-15
EB-12si-15; CPT-16-15
EB-09si-15; H-13vwp-15; CPT-19-15
N

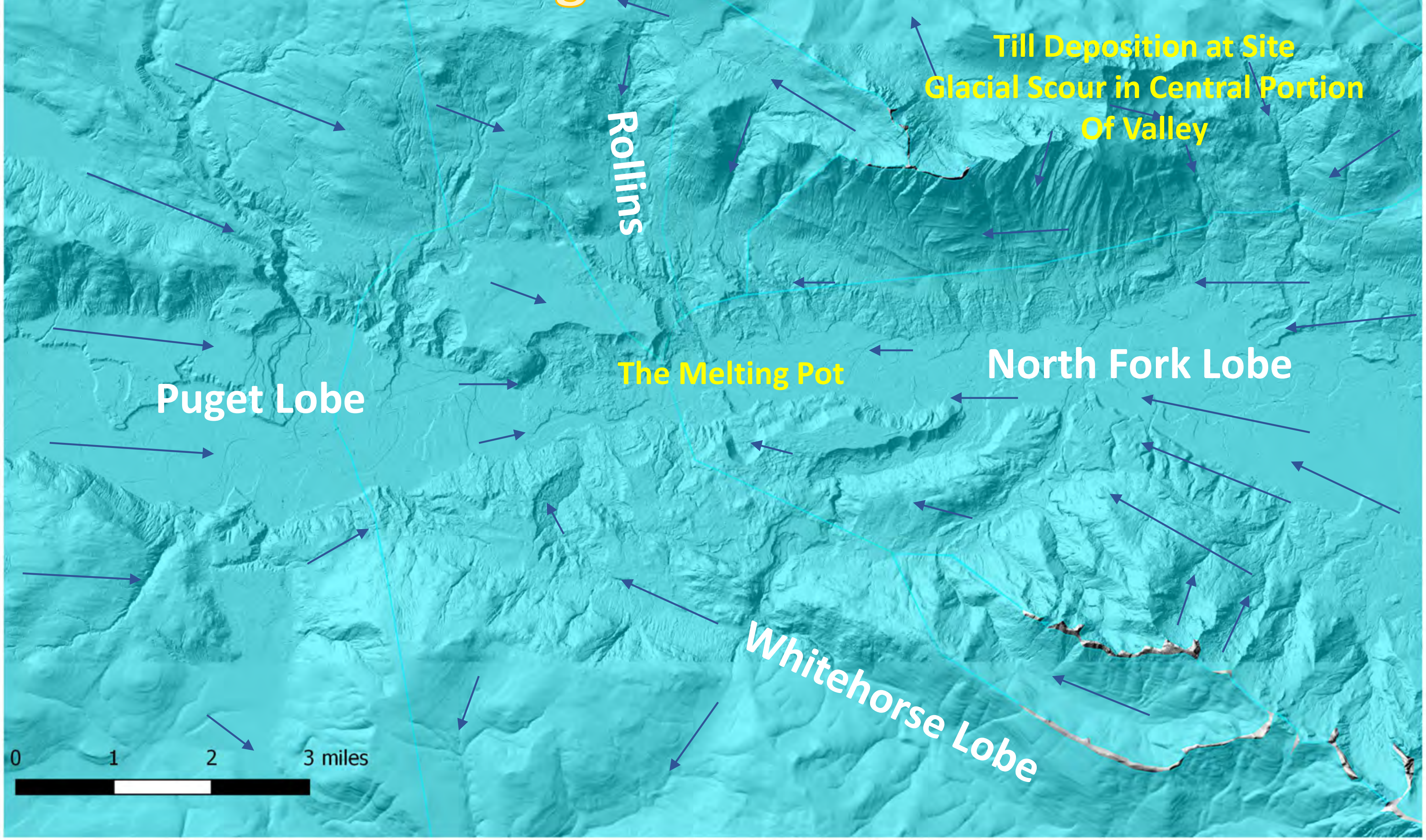

Flame Structures in Deformation Till in
Bear Lake Rhythmites
EB-07 (64-66')


Bear Lake Sand
Over-consolidated, Sheared Silt/Clay Rhythmite Interbed. Deformation Till

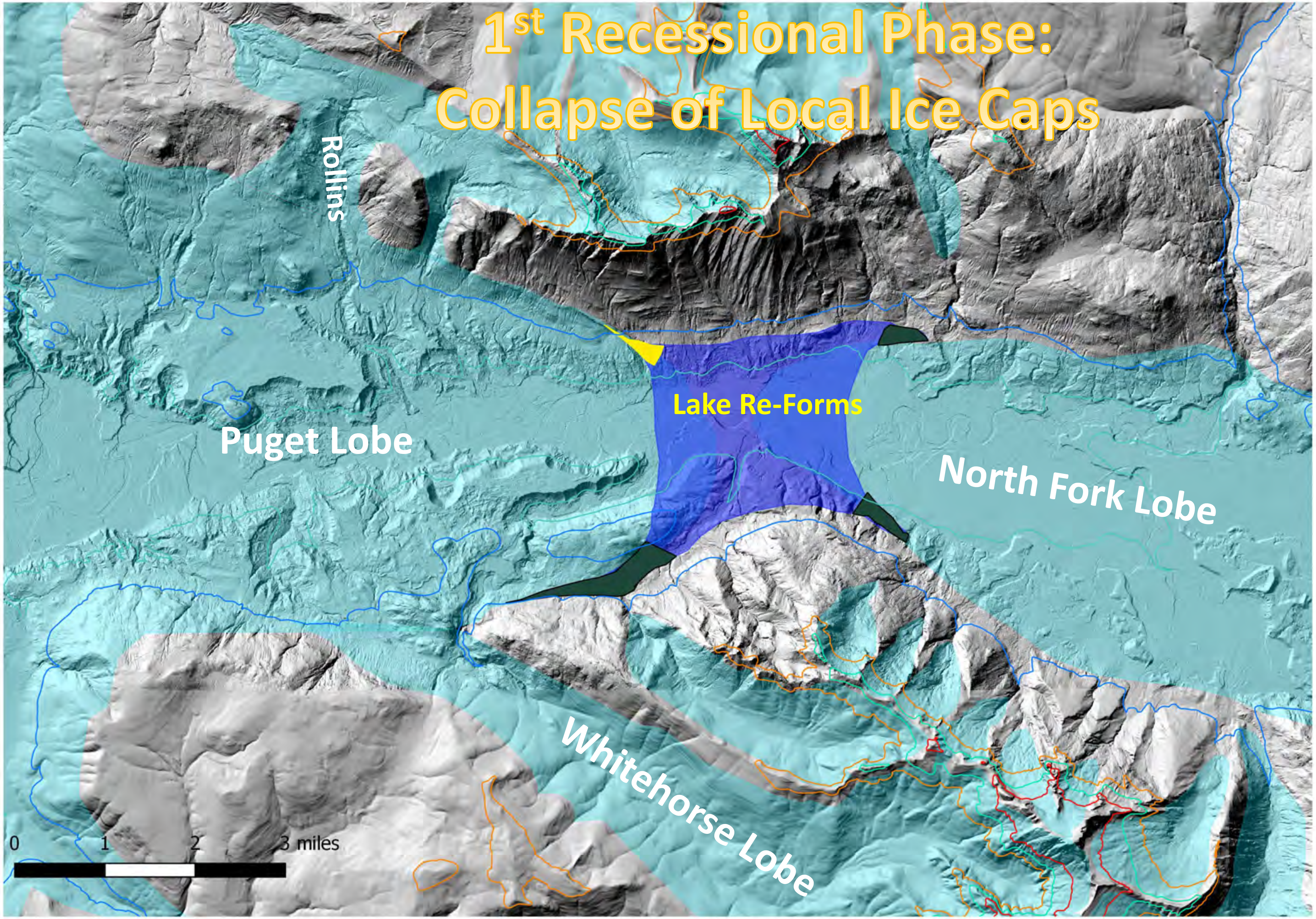

"Kissing Glaciers"
Or
"Glacial Gridlock"
Deposition at the Site All But Ceases
Some Glacial Scour of Sediments Starts
In Central Portion of Valley
Rollins
Puget Lobe
The Melting Pot
North Fork Lobe
Whitehorse Lobe
0
1
2
3 miles

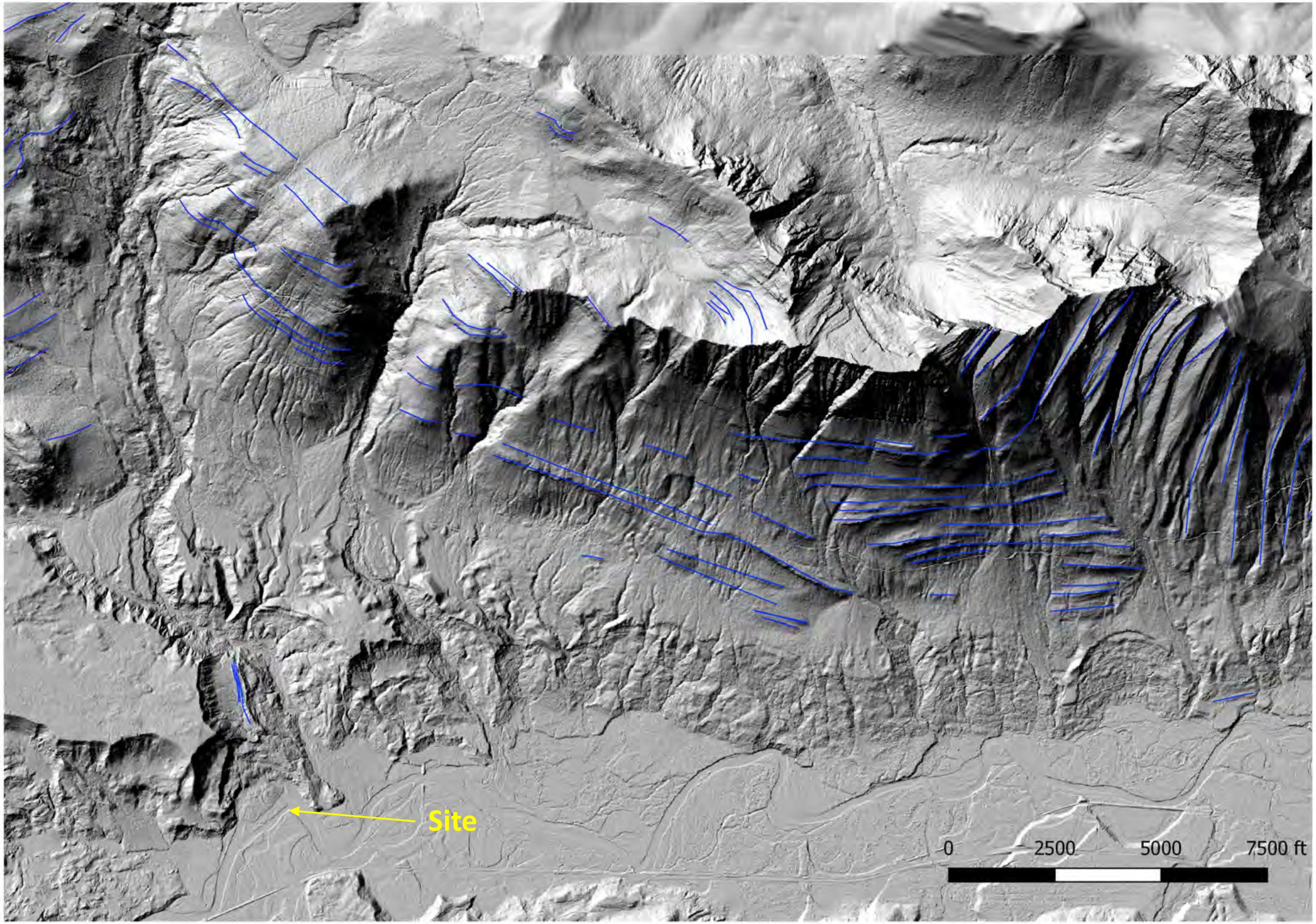

NW
Section 7 Extended
SE
Initial Lodgment Till Deposition at Site (+/-18,000 YBP?)
Rollins Ck. Lobe
North Fork Lobe
Puget Lobe?
White Horse Lobe
Bear Lake
Bear Lake Sand
4000
3500
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000

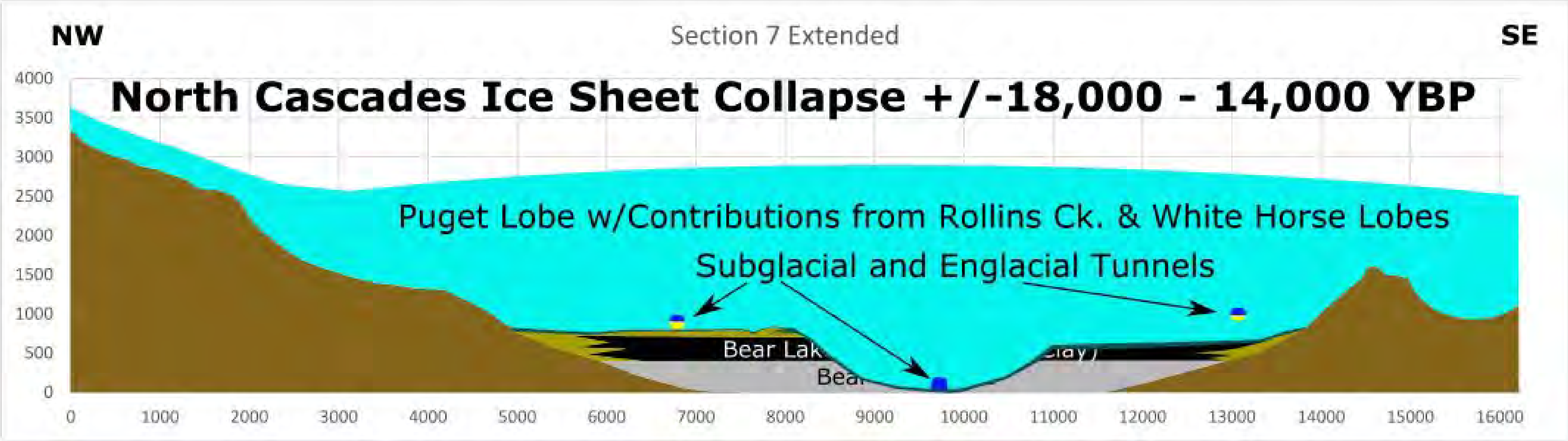
Glacial Maximum (18K to 14K Years Ago): Age of Nunataks

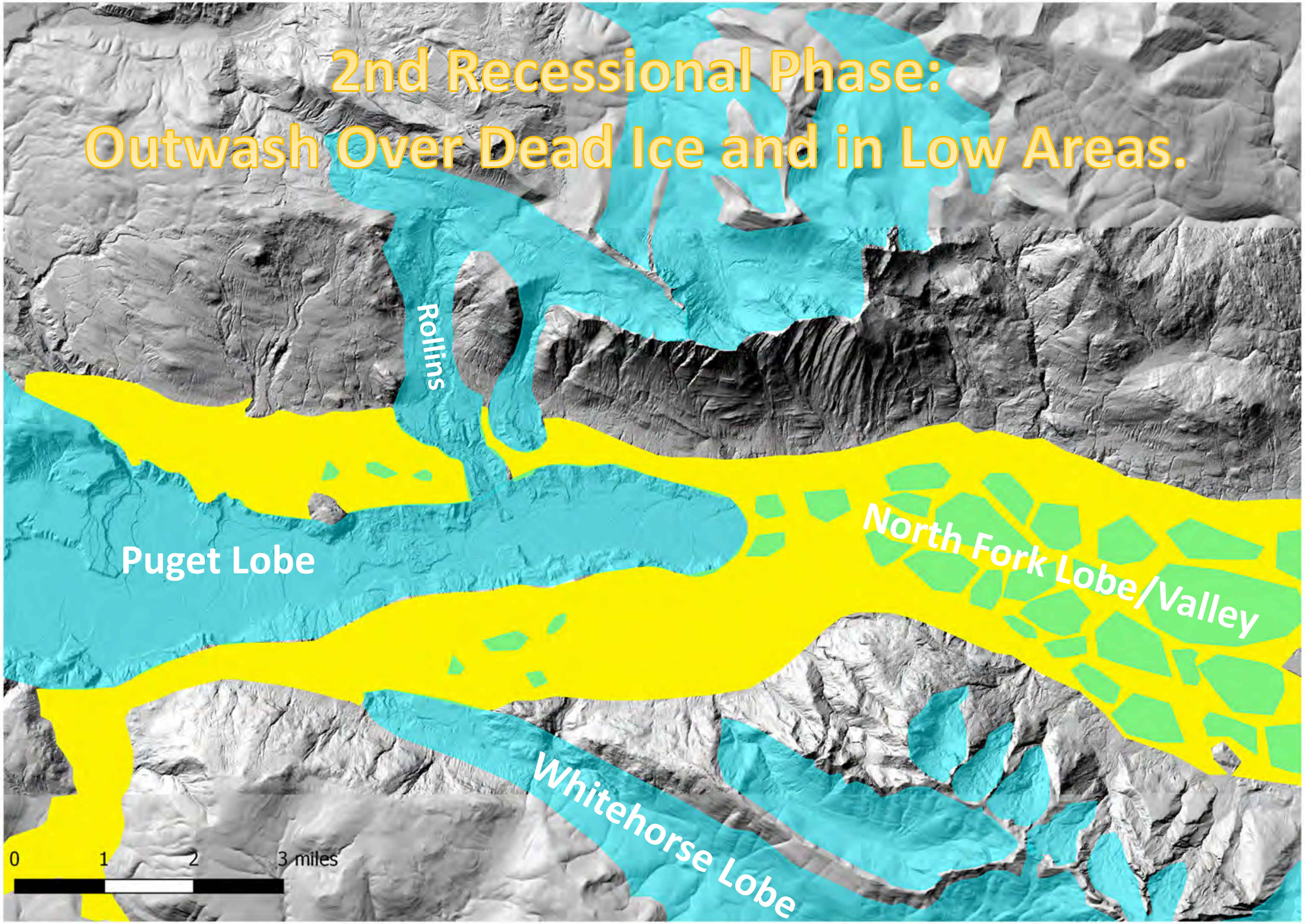


NW
Glacial Maximum (+/-18,000 YBP?)
SE
Combined (Confluent) Glaciers
Rollins Ck., North Fork, Puget, & White Horse Lobes
4000
3500
3000
2500
2000
1500
1000
500
0
Depth Unknown
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000

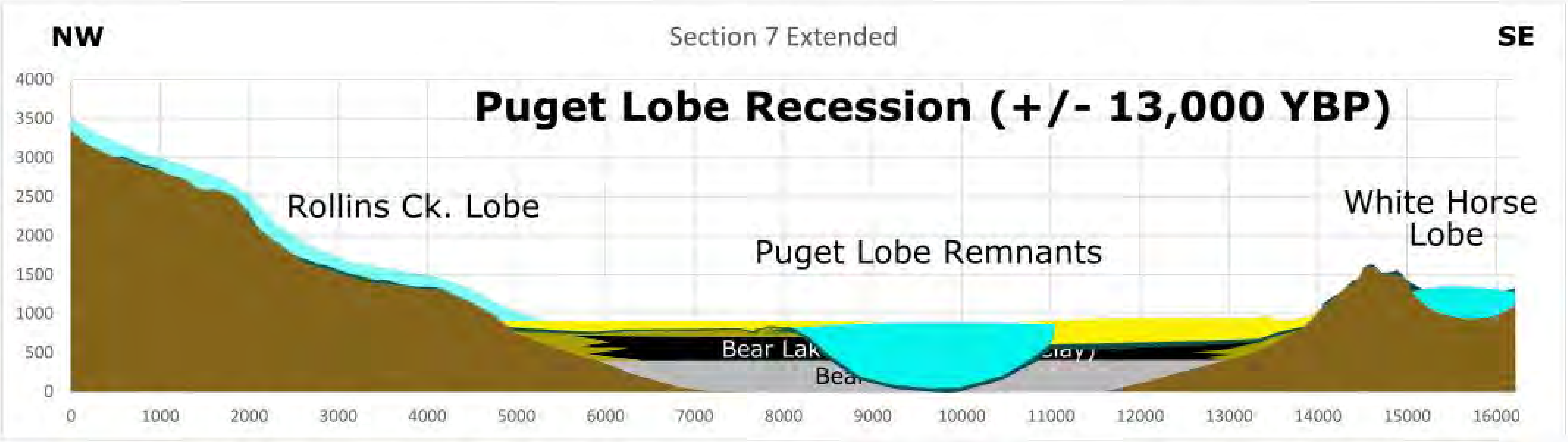

1st Recessional Phase:
Collapse of Local Ice Caps
Rollins
Lake Re-Forms
Puget Lobe
North Fork Lobe
Whitehorse Lobe
0
1
2
3 miles


Site
0
2500
5000
7500 ft


NW
Section 7 Extended
SE
North Cascades Ice Sheet Collapse +/-18,000 - 14,000 YBP
Puget Lobe w/Contributions from Rollins Ck. & White Horse Lobes
Subglacial and Englacial Tunnels
Bear Lak
Bea
4000
3500
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000



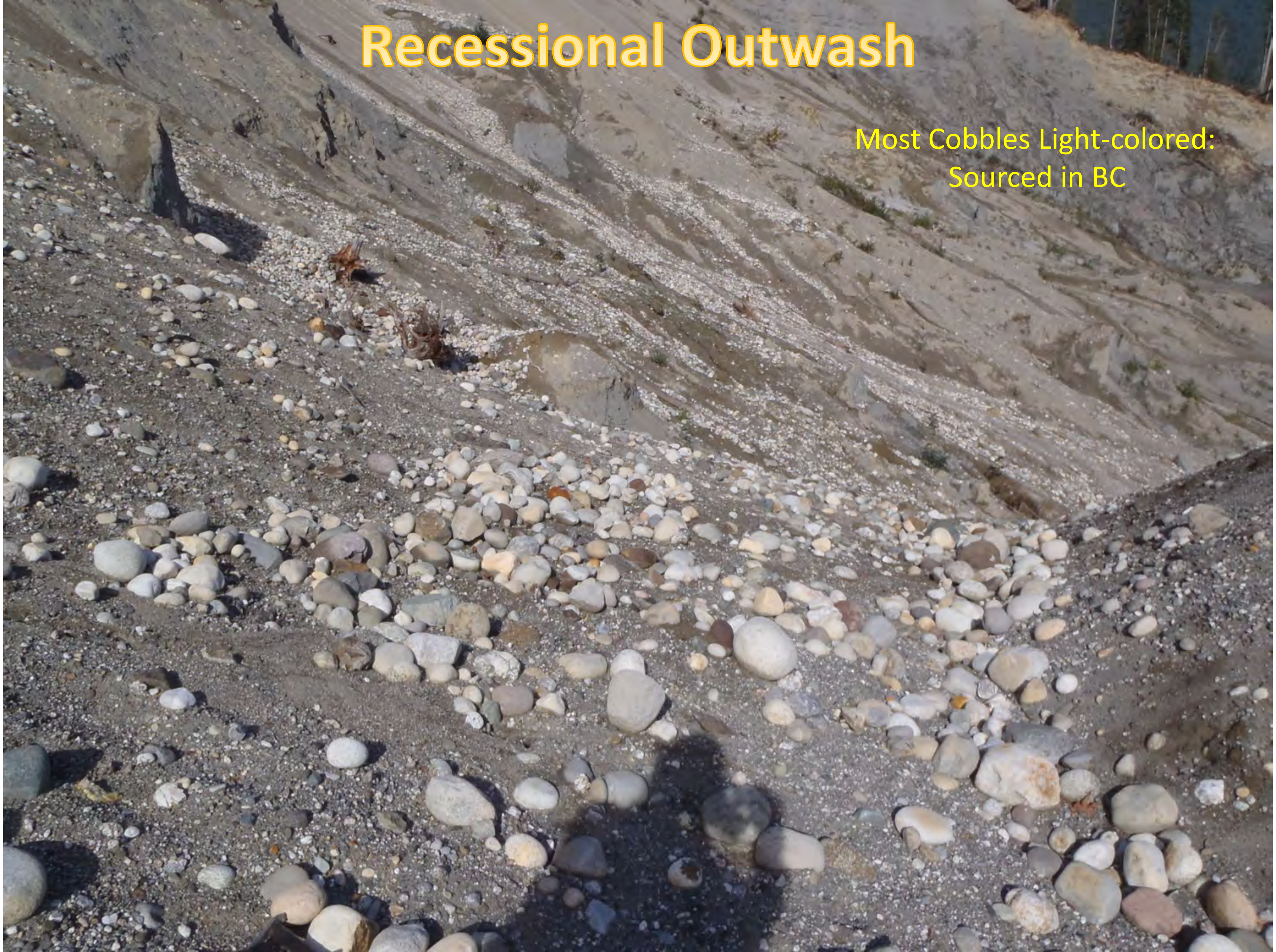
2nd Recessional Phase:
Outwash Over Dead Ice and in Low Areas.
Rollins
Puget Lobe
North Fork Lobe/Valley
Whitehorse Lobe
0
1
2
3 miles



NW
Section 7 Extended
SE
Puget Lobe Recession (+/- 13,000 YBP)
Rollins Ck. Lobe
Puget Lobe Remnants
White Horse Lobe
Bear Lak
Bea
4000
3500
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000


Recessional Outwash
Mostly Tan to Orange Sand with Light-Colored Pebbles and Cobbles

Recessional Outwash

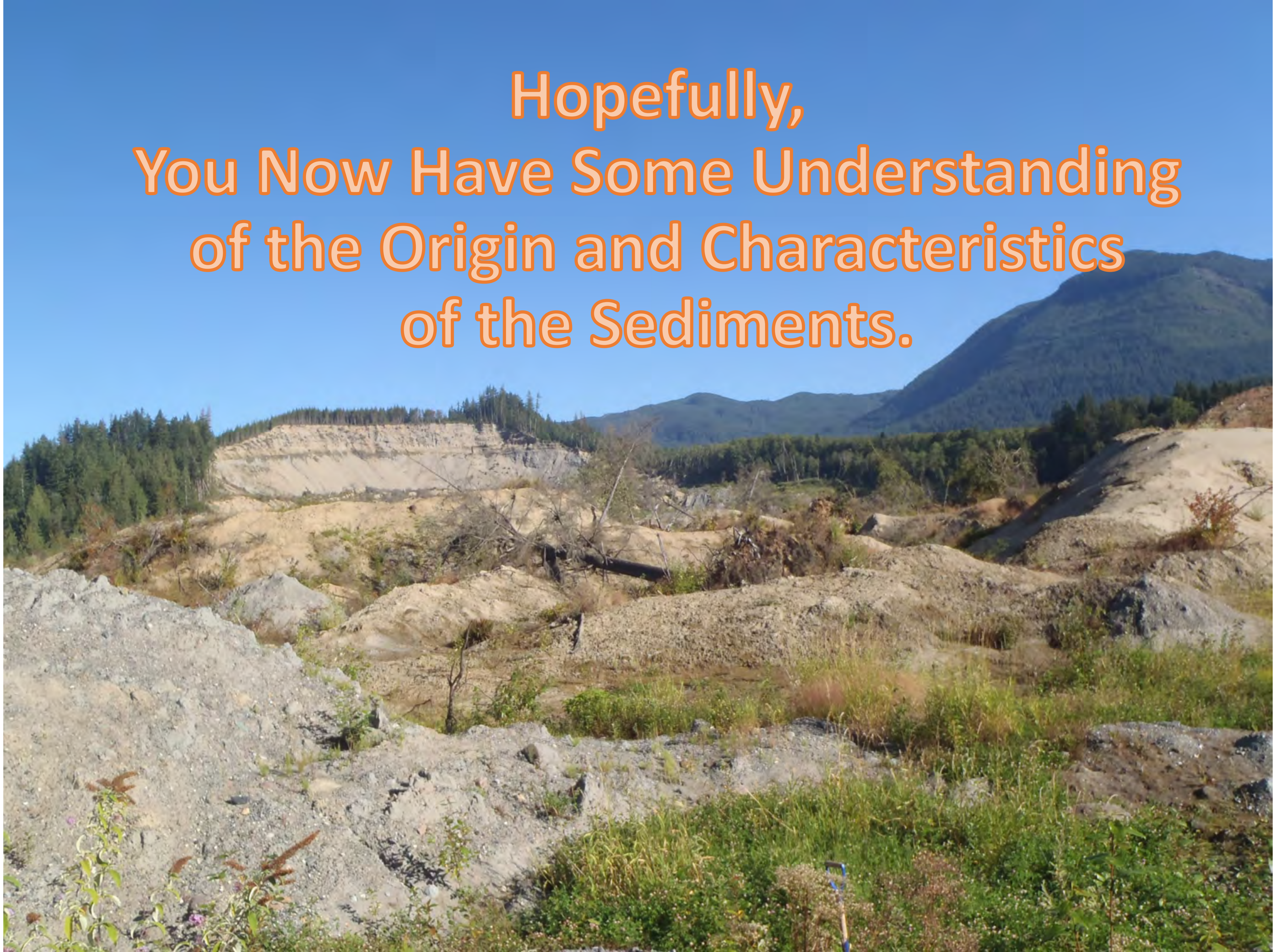


Most Cobbles Light-colored:
Sourced in BC

Recessional Outwash


Recessional Outwash
Extended Forest Floor and Transported Alders

Recessional Outwash in Central Head-scarp


Hopefully,
You Now Have Some Understanding
of the Origin and Characteristics
of the Sediments.

WHY DID YOU NEED TO KNOW THIS?

- **This information provides the framework for the how and why of the Oso slide.**
- **Without this knowledge, there is no basis for opinions regarding reasons for "Oso."**
- **If you cannot determine reasons, you cannot know what "went wrong".**
- **If you don't know what went wrong,**

    You cannot know if, where, and why it might happen again.

    You cannot develop effective guidelines for this and similar sites.

    You cannot assign or refute blame as appropriate.

IN PART 2 WE WILL:

- Find out How we Arrived at March 22, 2014 (and see some of the evidence).
- Find out What Happened in the 2 Minutes it Took the Oso Slide to Move a Mile, Along with Some of the Evidence for this Interpretation.
- Find out What's Happened Since.
- Discuss Ramifications?


PART 2:
And Now we Diverge
From Another Dominant Paradigm

The Dominant Paradigm

BACKGROUND

When the Cordilleran ice sheet advanced southward into the Puget Sound ~17,500 yr ago, it dammed rivers flowing west from the Cascade Mountains (Porter and Swanson, 1998), filling the North Fork Stillaguamish River (NFSR) valley with 200 m of glacial sediment. Geologic mapping indicates that numerous landslides have occurred in this sediment (Dragovich et al., 2003), which is characterized by low-permeability glaciolacustrine clays overlain by sandy advance outwash, till, and gravelly recessional outwash (Keaton et al., 2014; Riemer et al., 2015). Similar stratigraphy is prevalent in the region and is well known to be landslide prone during and soon after high-intensity or long-duration precipitation (Chleborad, 2000; Coe et al., 2004).

Following ice retreat ~16.4 k.y. ago (Porter and Swanson, 1998; Beechie et al., 2001), the NFSR began incising rapidly into these mechanically weak glacial deposits, creating the modern valley relief and setting the stage for long-standing slope instability in the area.

Geology, published online on 22 December 2015 as doi:10.1130/G37267.1

Surface roughness dating of long-runout landslides near Oso, Washington (USA), reveals persistent postglacial hillslope instability

Sean R. LaHusen[1], Alison R. Duvall[1], Adam M. Booth[2], and David R. Montgomery[1]
[1]Department of Earth and Space Sciences, University of Washington, Box 351310, Seattle, Washington 98195, USA
[2]Department of Geology, Portland State University, 1721 SW Broadway, Portland, Oregon, 97201 USA

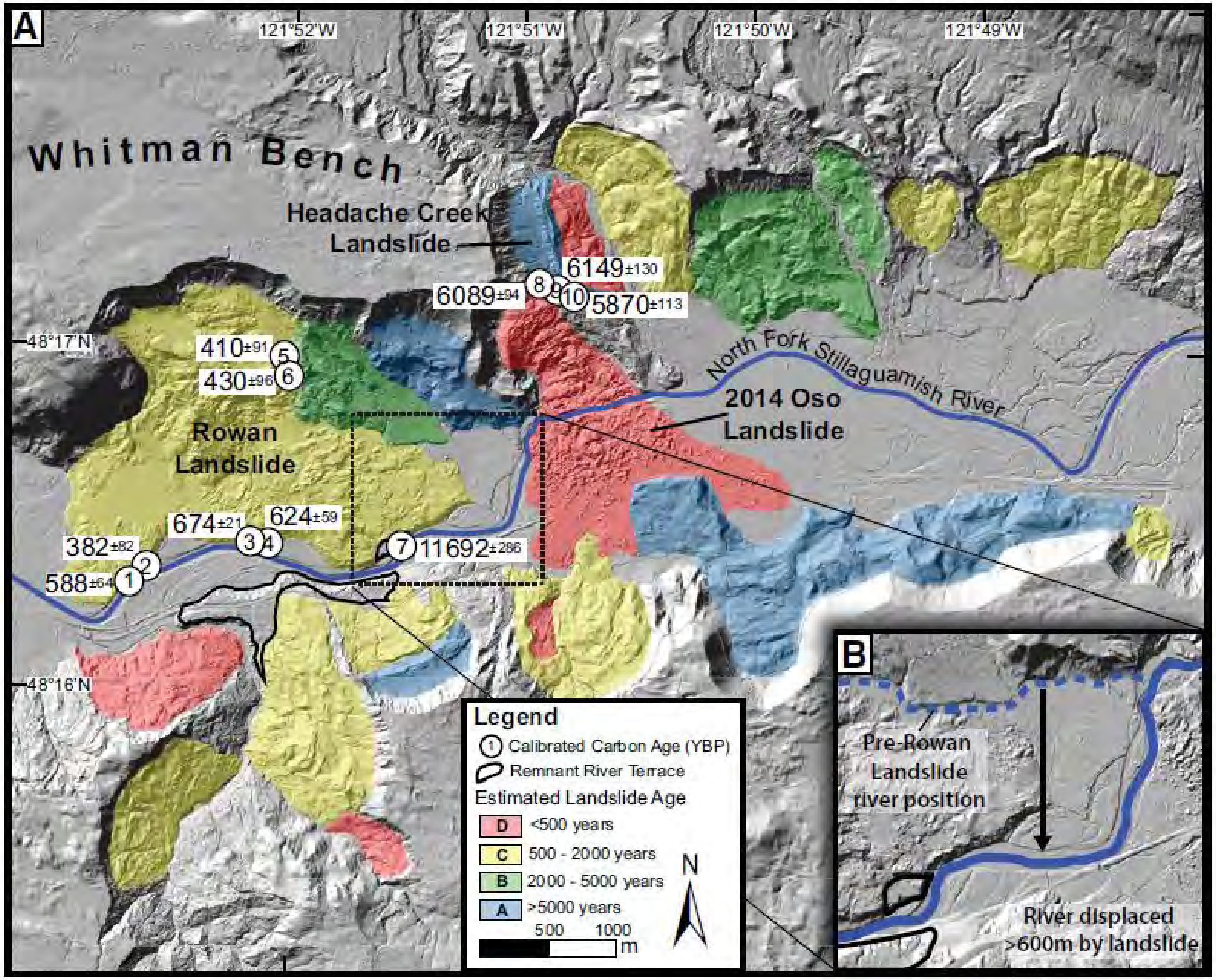
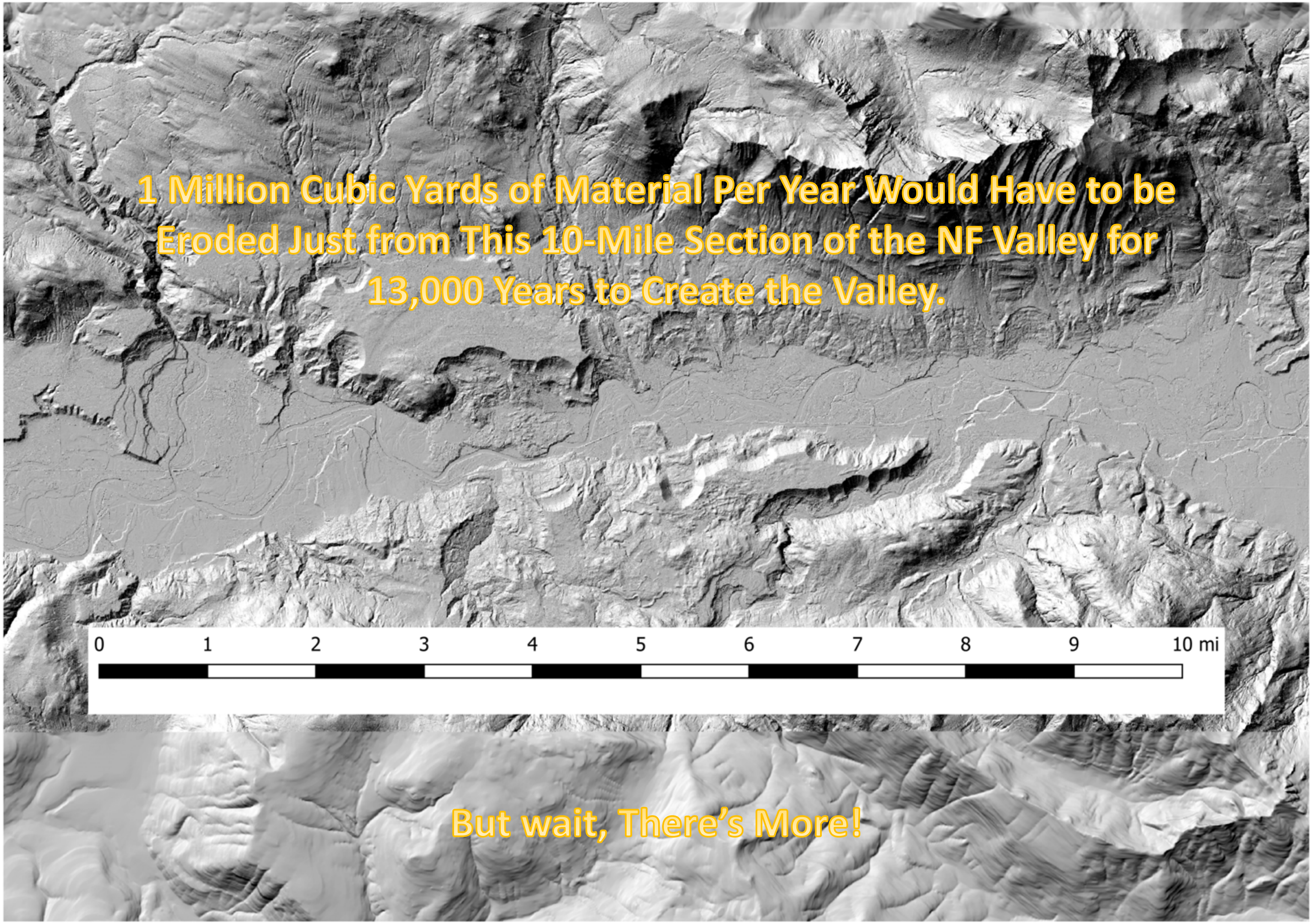


Figure 3. A: Lidar bare-earth imagery of the study area, showing all mapped landslides colored by estimated age. Landslides are binned into four age classes (7 class A, 3 class B, 10 class C, and 5 class D; see text) based on estimated age from the surface roughness-age regression. Predicted age classes agree well with crosscutting relationships between landslides. cal yr B.P.—years before present (present = 1950). B: Blow-up map showing inferred river position (dashed line) prior to the Rowan landslide (Washington State, USA) ca. 500 ^{14}C yr B.P., based on erosional contact on an older landslide deposit. The current river position (solid line) suggests that the active channel was displaced at least 600 m when the Rowan landslide occurred.


1 Million Cubic Yards of Material Per Year Would Have to be Eroded Just from This 10-Mile Section of the NF Valley for 13,000 Years to Create the Valley.
0
1
2
3
4
5
6
7
8
9
10 mi
But wait, There's More!

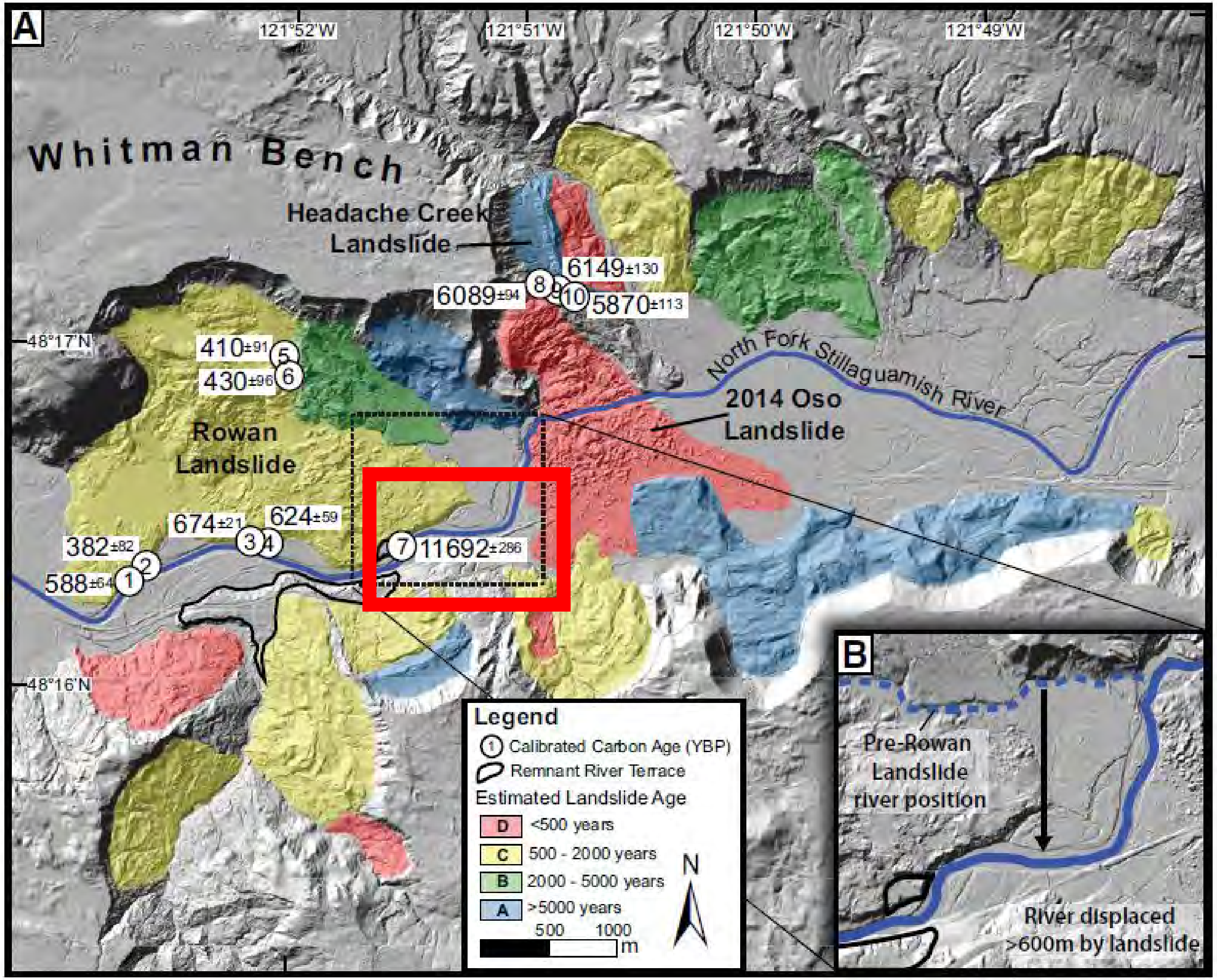
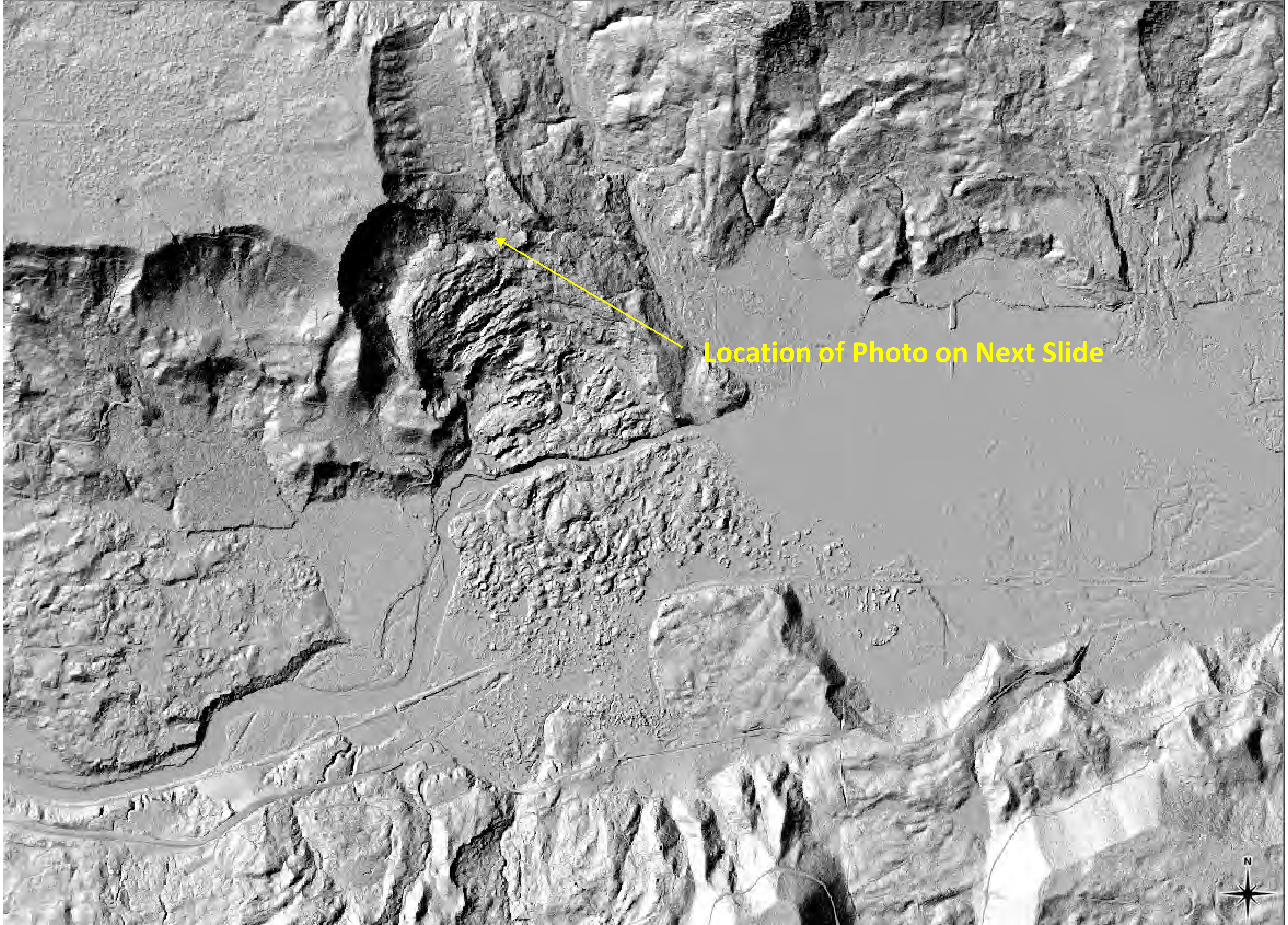


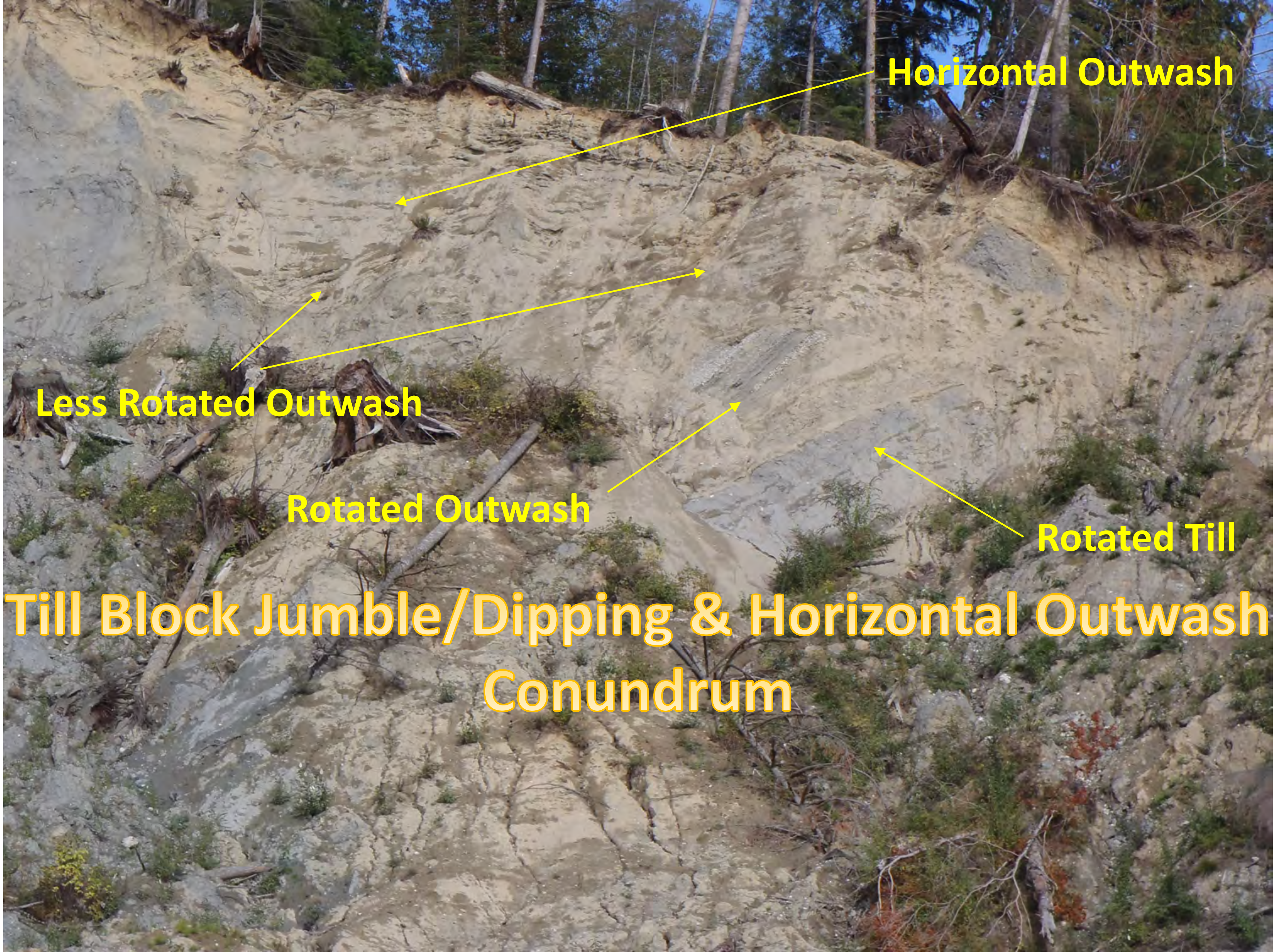
Figure 3. A: Lidar bare-earth imagery of the study area, showing all mapped landslides colored by estimated age. Landslides are binned into four age classes (7 class A, 3 class B, 10 class C, and 5 class D; see text) based on estimated age from the surface roughness-age regression. Predicted age classes agree well with crosscutting relationships between landslides. cal yr B.P.—years before present (present = 1950). B: Blow-up map showing inferred river position (dashed line) prior to the Rowan landslide (Washington State, USA) ca. 500 ^{14}C yr B.P., based on erosional contact on an older landslide deposit. The current river position (solid line) suggests that the active channel was displaced at least 600 m when the Rowan landslide occurred.

This Means 5 – 10 Million Cubic Yards per Year Must be Removed from 10-Mile Stretch (from +/- 13,000 to 11,692 YBP).

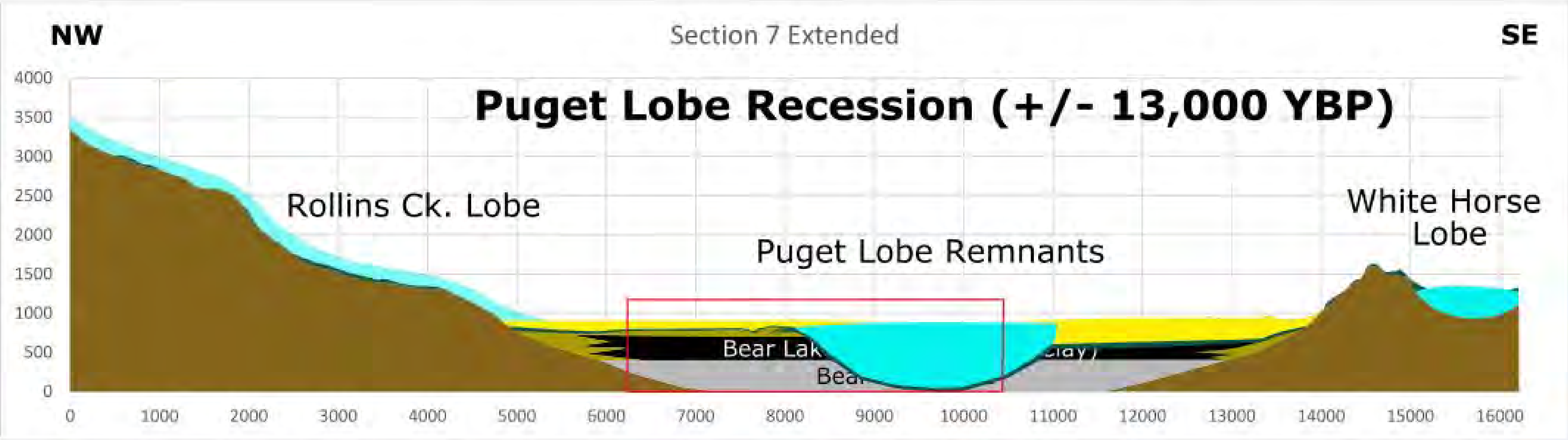
But There is Another Way!



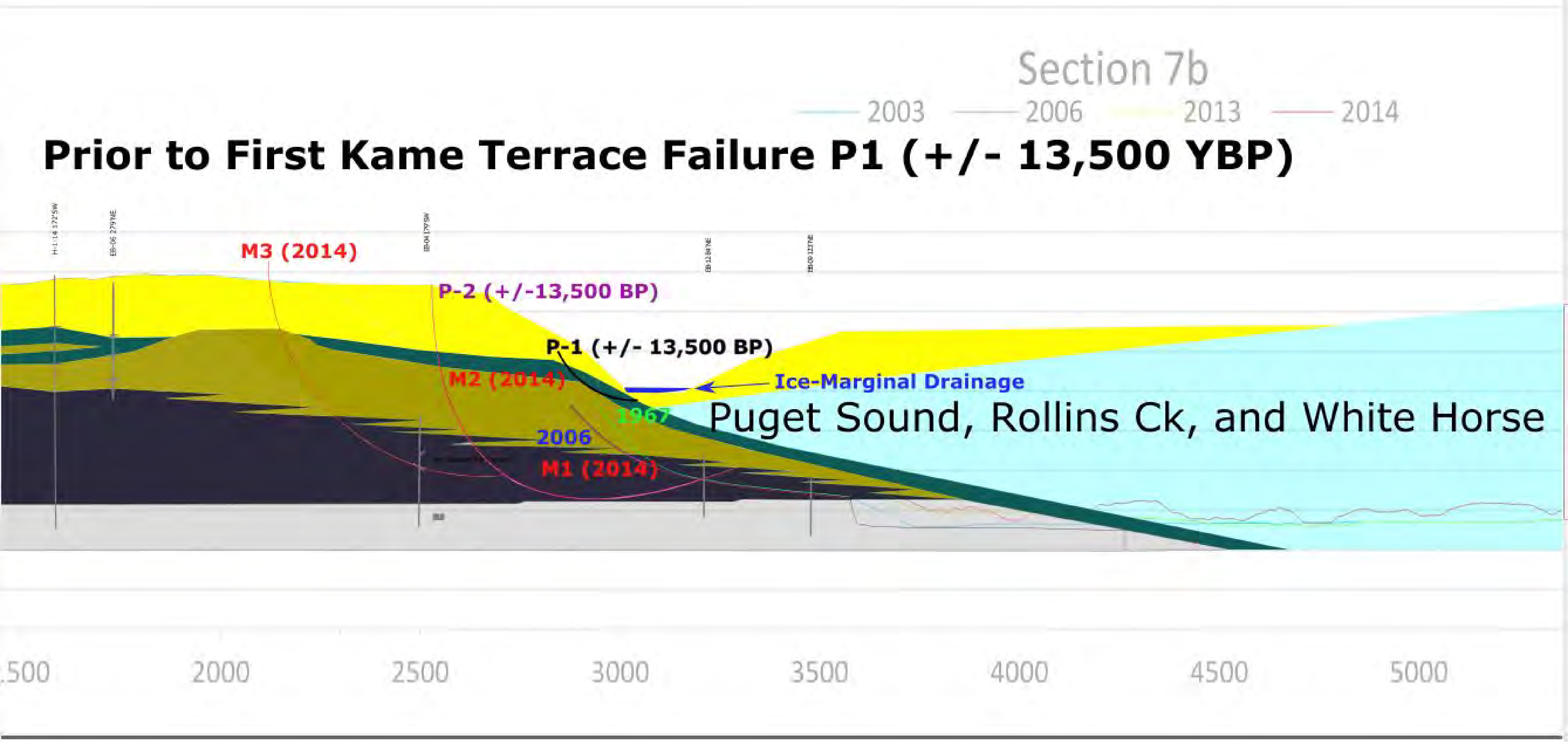
Location of Photo on Next Slide
N

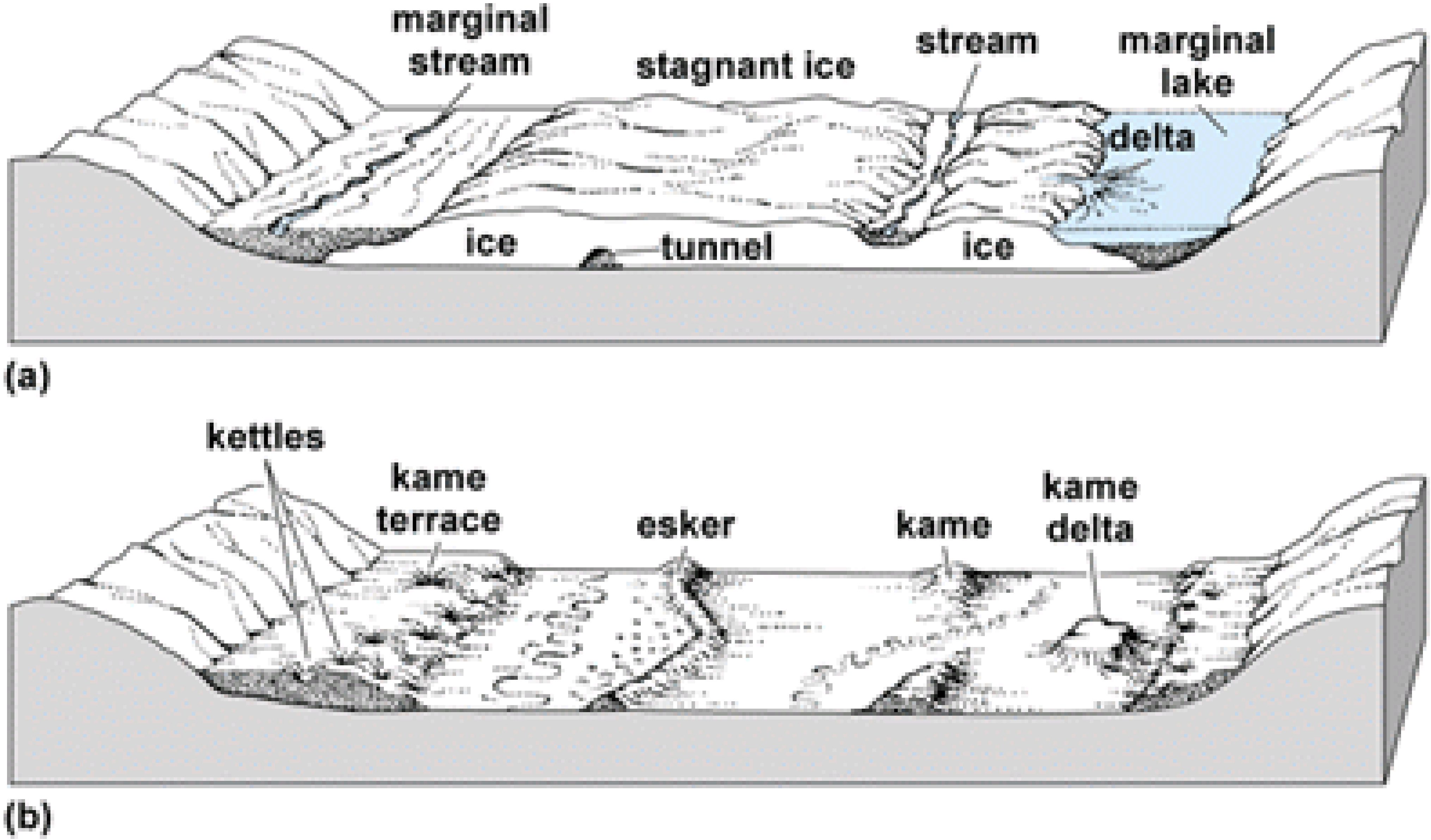


Horizontal Outwash
Less Rotated Outwash
Rotated Outwash
Rotated Till
Till Block Jumble/Dipping & Horizontal Outwash
Conundrum



NW
Section 7 Extended
SE
Puget Lobe Recession (+/- 13,000 YBP)
Rollins Ck. Lobe
White Horse Lobe
Puget Lobe Remnants
Bear Lak
Bea
4000
3500
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000

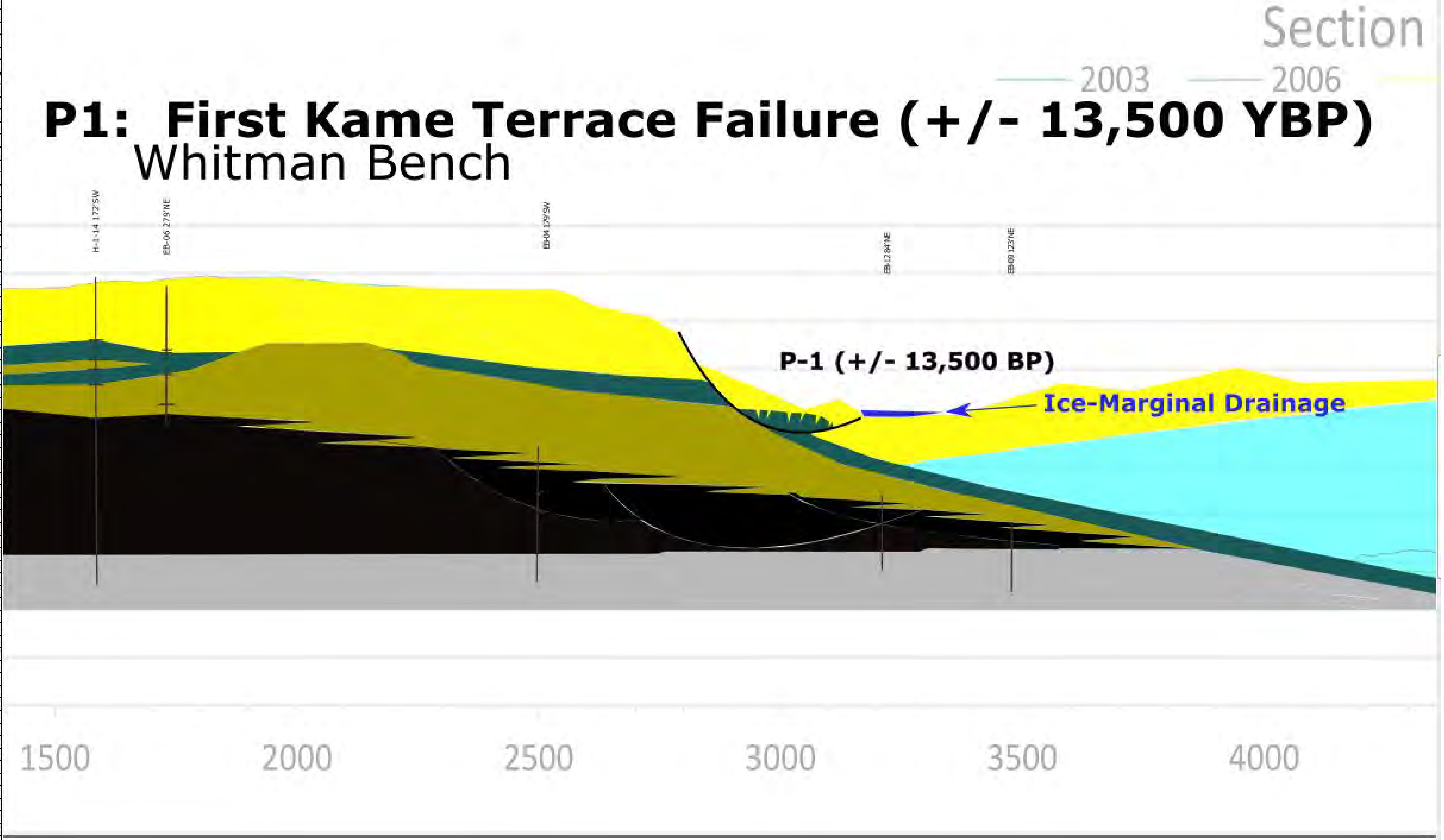

Section 7b
2003
2006
2013
2014
Prior to First Kame Terrace Failure P1 (+/- 13,500 YBP)
M3 (2014)
P-2 (+/-13,500 BP)
P-1 (+/- 13,500 BP)
M2 (2014)
Ice-Marginal Drainage
1967
Puget Sound, Rollins Ck, and White Horse
2006
M1 (2014)
1500
2000
2500
3000
3500
4000
4500
5000

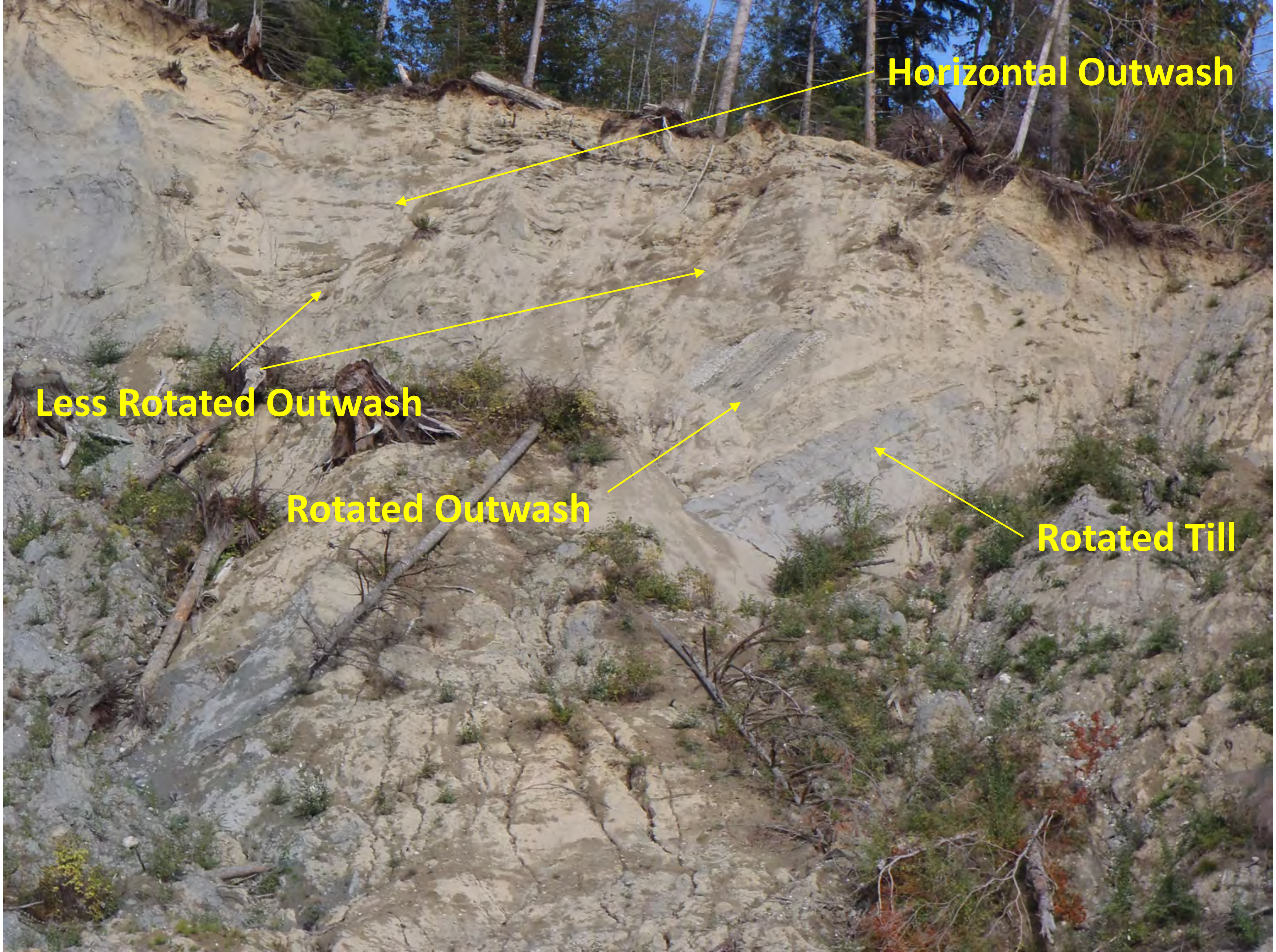


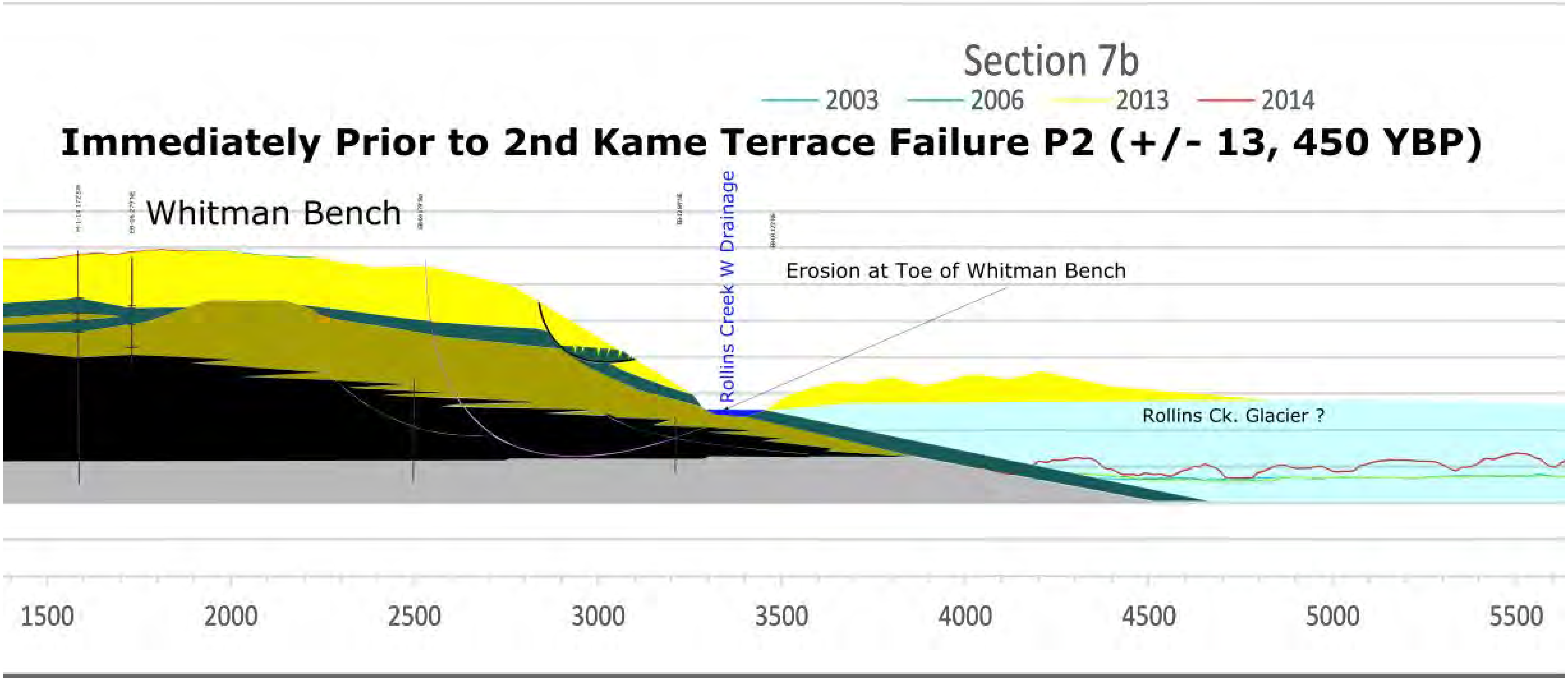
marginal stream
stagnant ice
stream
marginal lake
delta
ice
tunnel
ice
(a)
kettles
kame terrace
esker
kame
kame delta
(b)

P1: First Kame Terrace Failure (+/- 13,500 YBP)

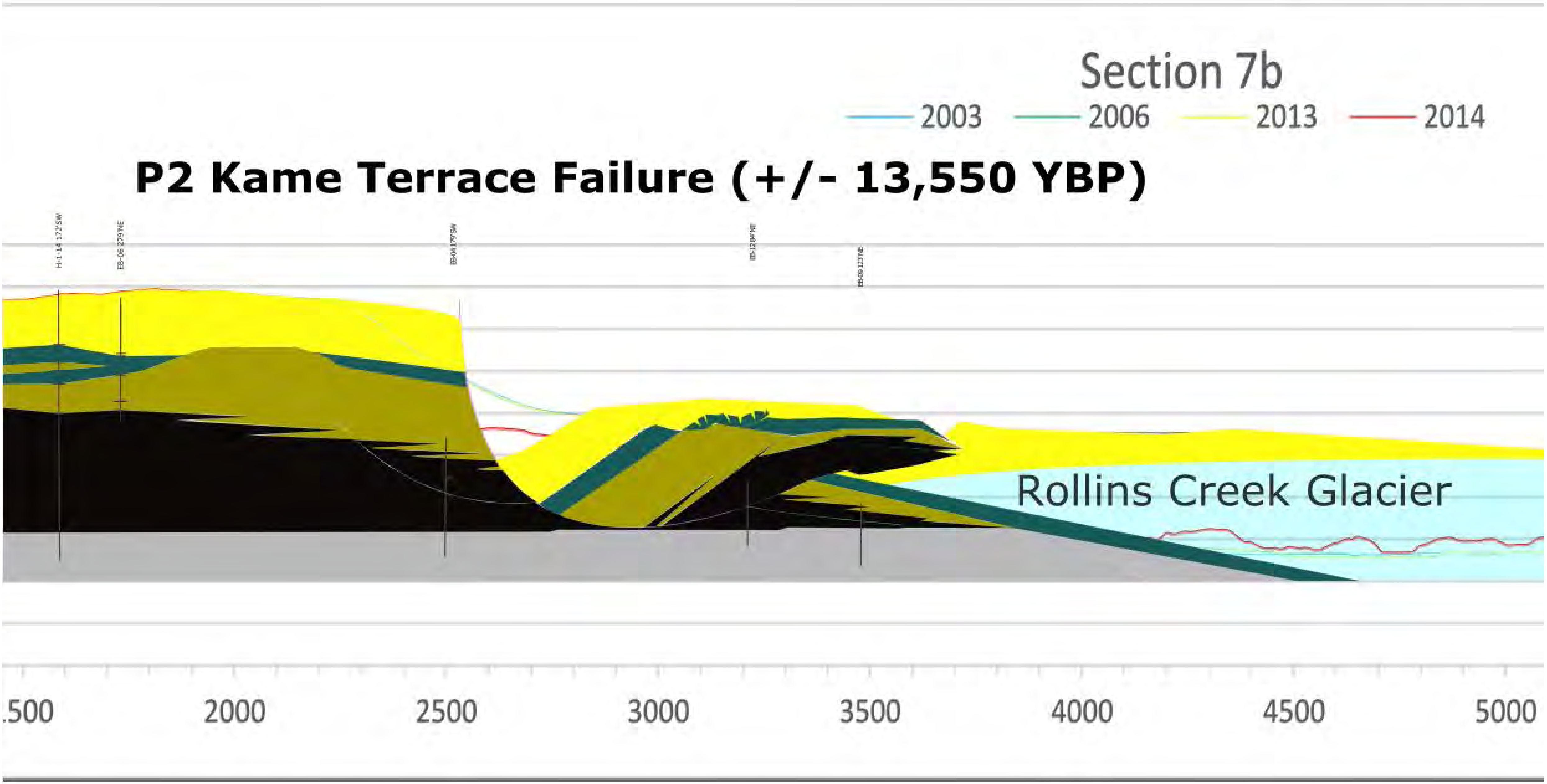
Whitman Bench

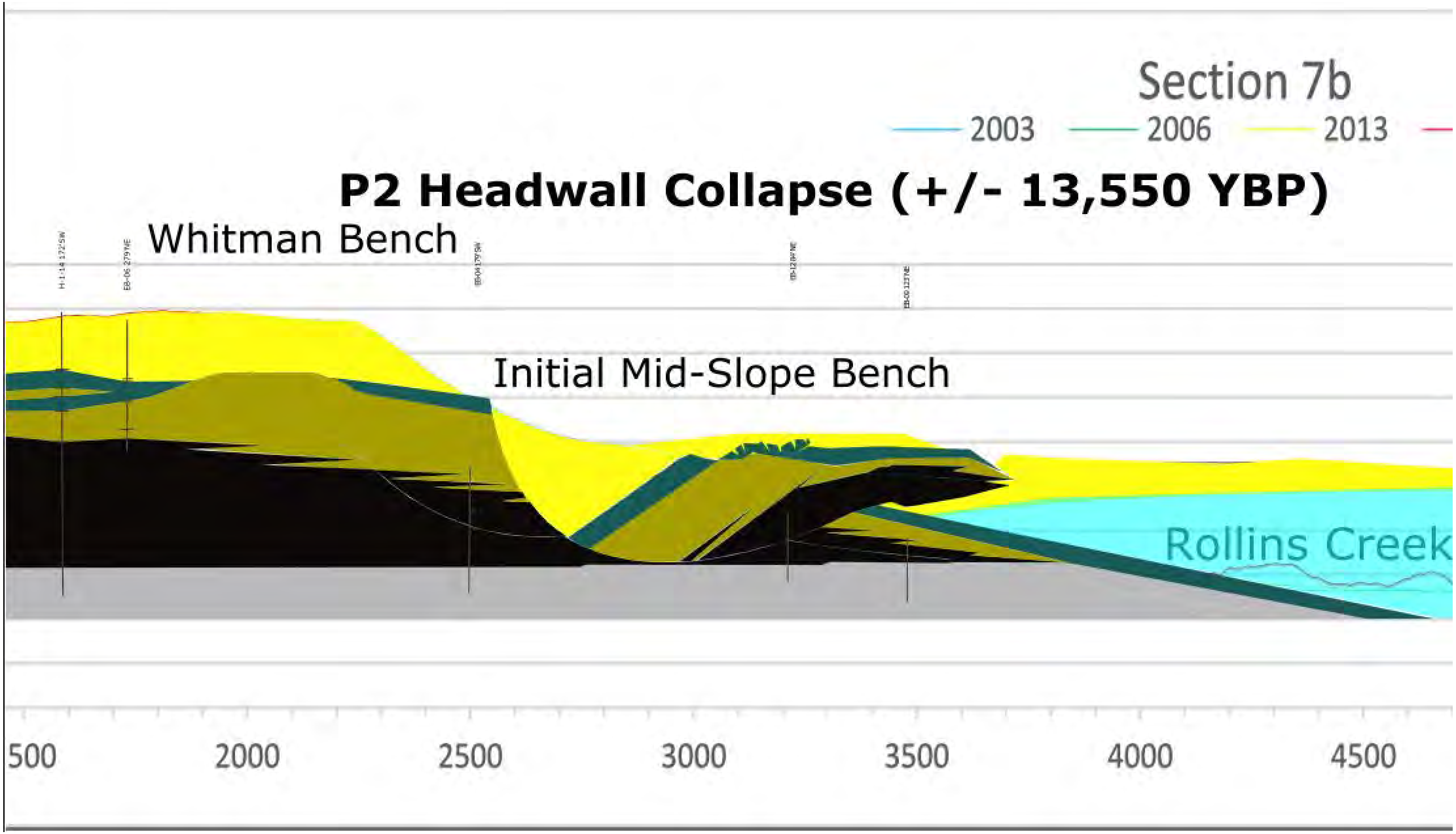


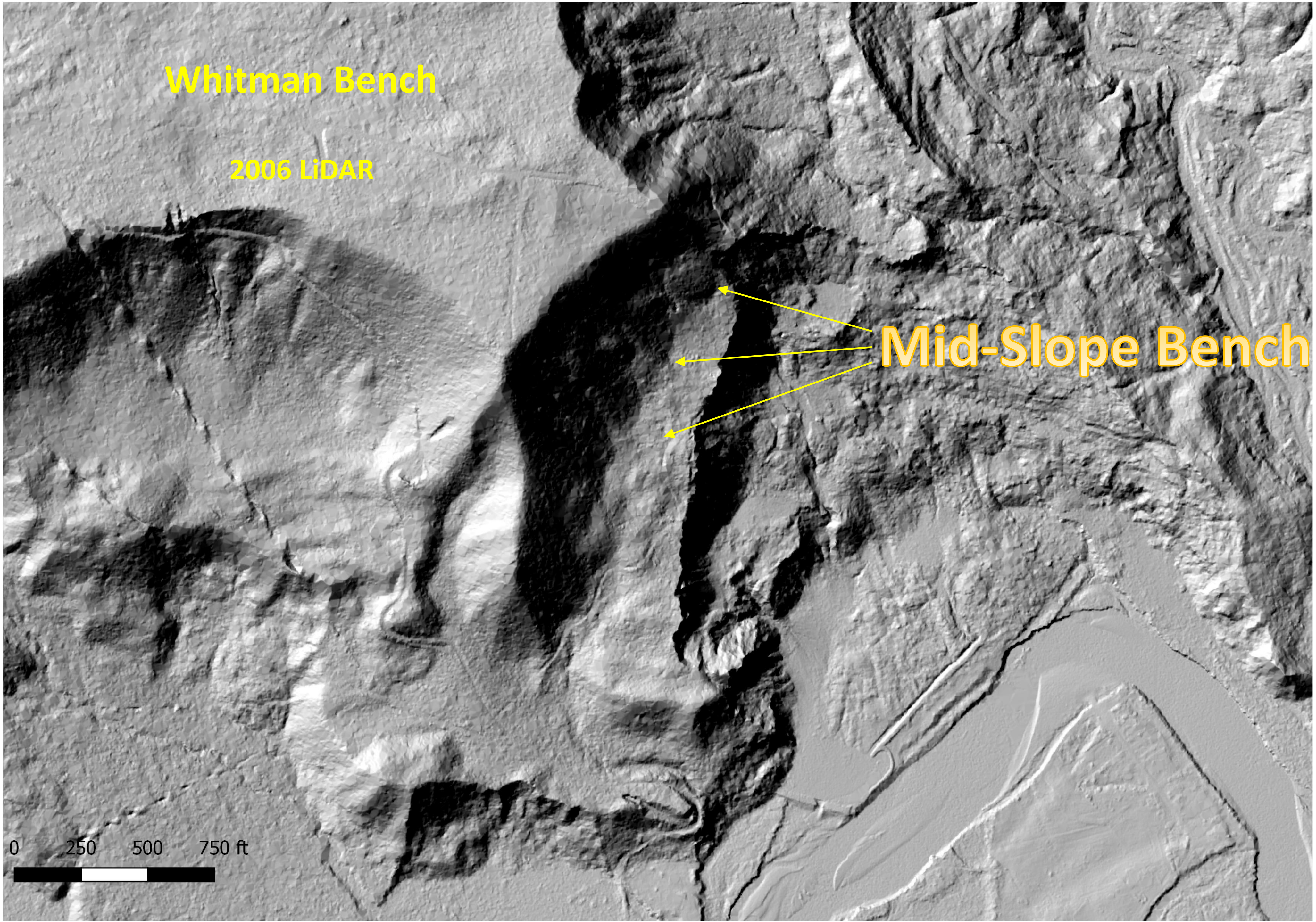

Horizontal Outwash
Less Rotated Outwash
Rotated Outwash
Rotated Till



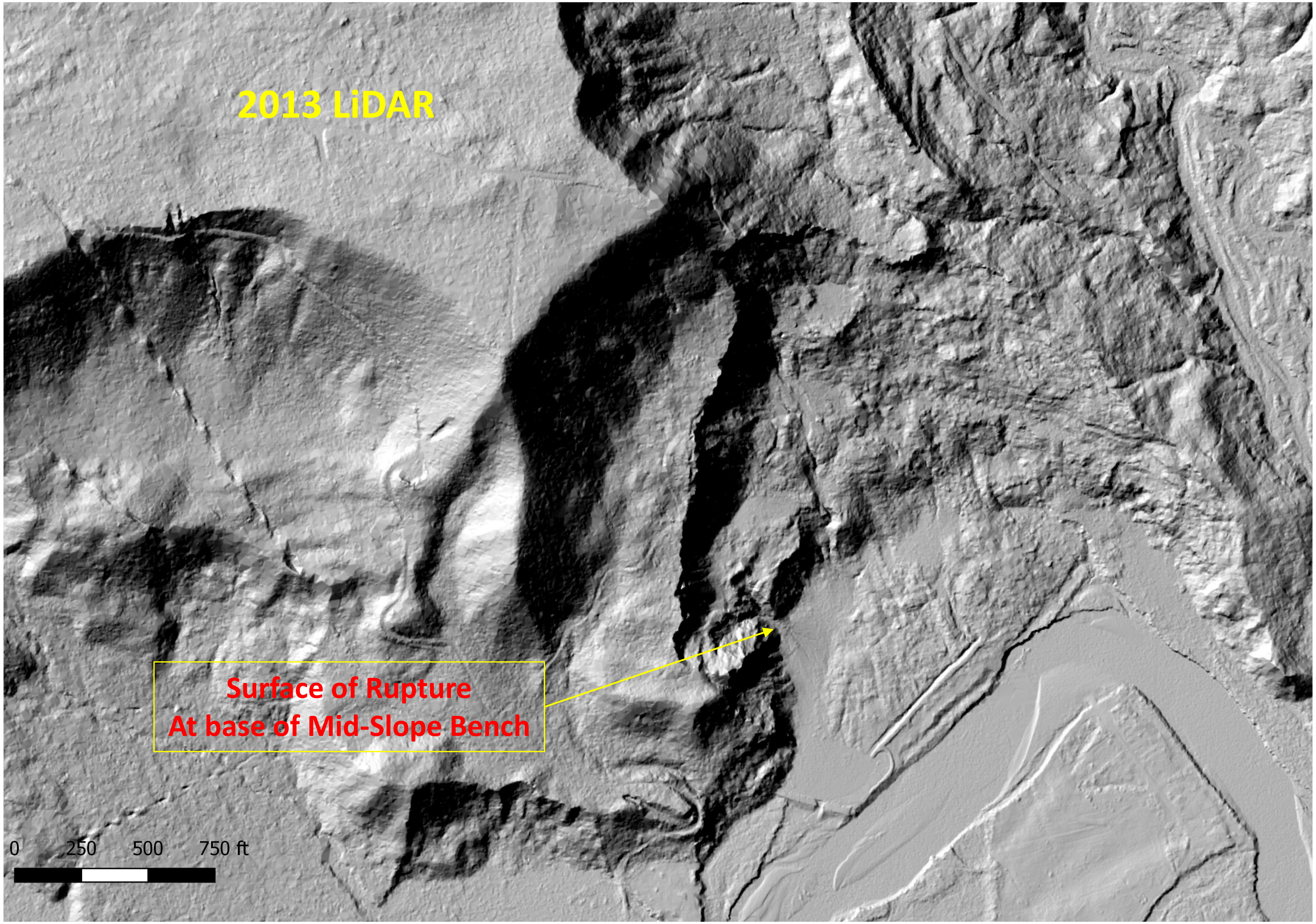
Section 7b
2003
2006
2013
2014
Immediately Prior to 2nd Kame Terrace Failure P2 (+/- 13, 450 YBP)
Whitman Bench
Rollins Creek W Drainage
Erosion at Toe of Whitman Bench
Rollins Ck. Glacier ?
1500
2000
2500
3000
3500
4000
4500
5000
5500


Section 7b
2003
2006
2013
2014
P2 Kame Terrace Failure (+/- 13,550 YBP)
Rollins Creek Glacier
.500
2000
2500
3000
3500
4000
4500
5000

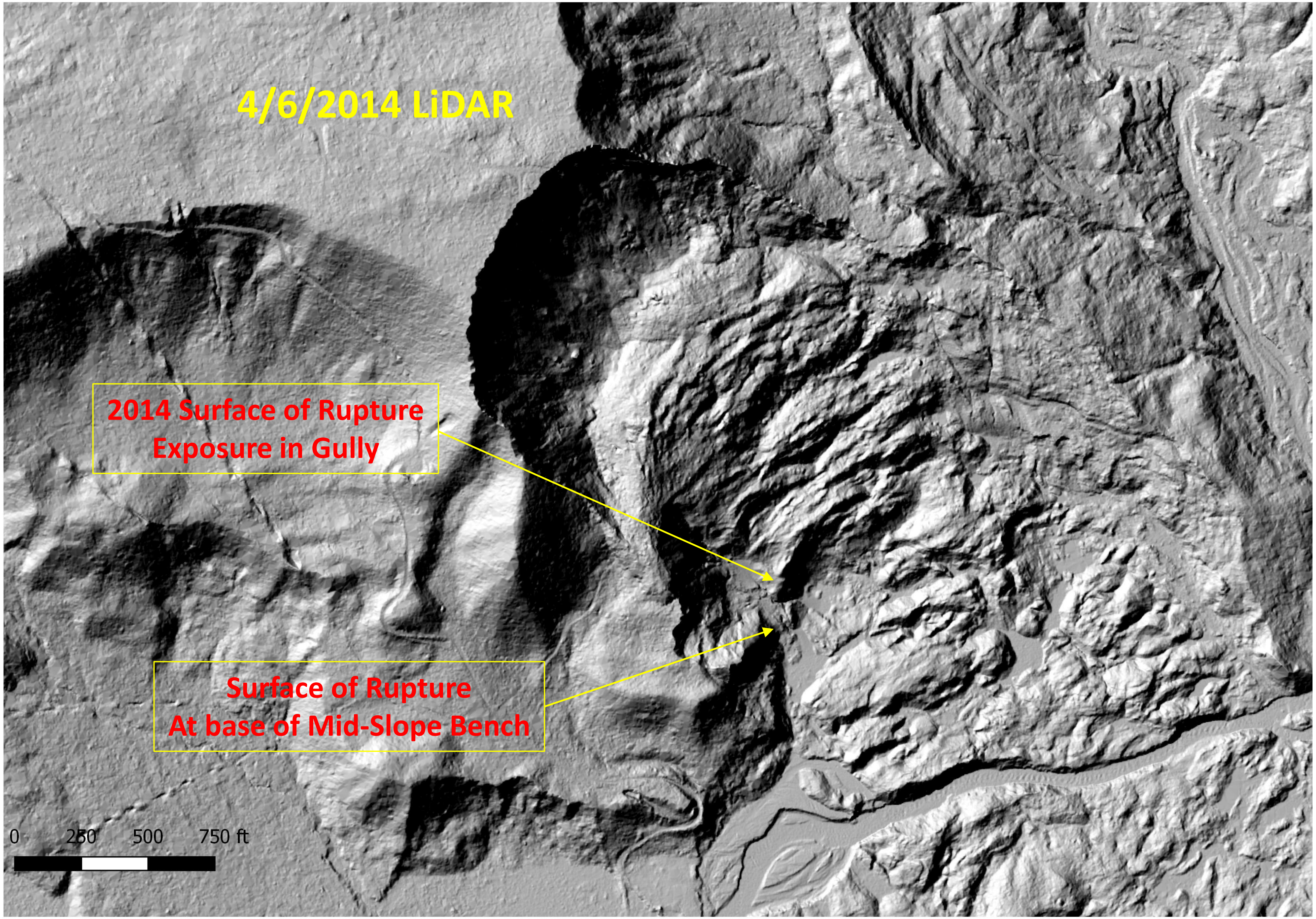

Section 7b
2003
2006
2013
P2 Headwall Collapse (+/- 13,550 YBP)
Whitman Bench
Initial Mid-Slope Bench
Rollins Creek
500
2000
2500
3000
3500
4000
4500


Whitman Bench
2006 LiDAR
Mid-Slope Bench
0
250
500
750 ft


Old Surface of Rupture at
Base of Remaining
Mid-Slope Bench Block,
West Margin

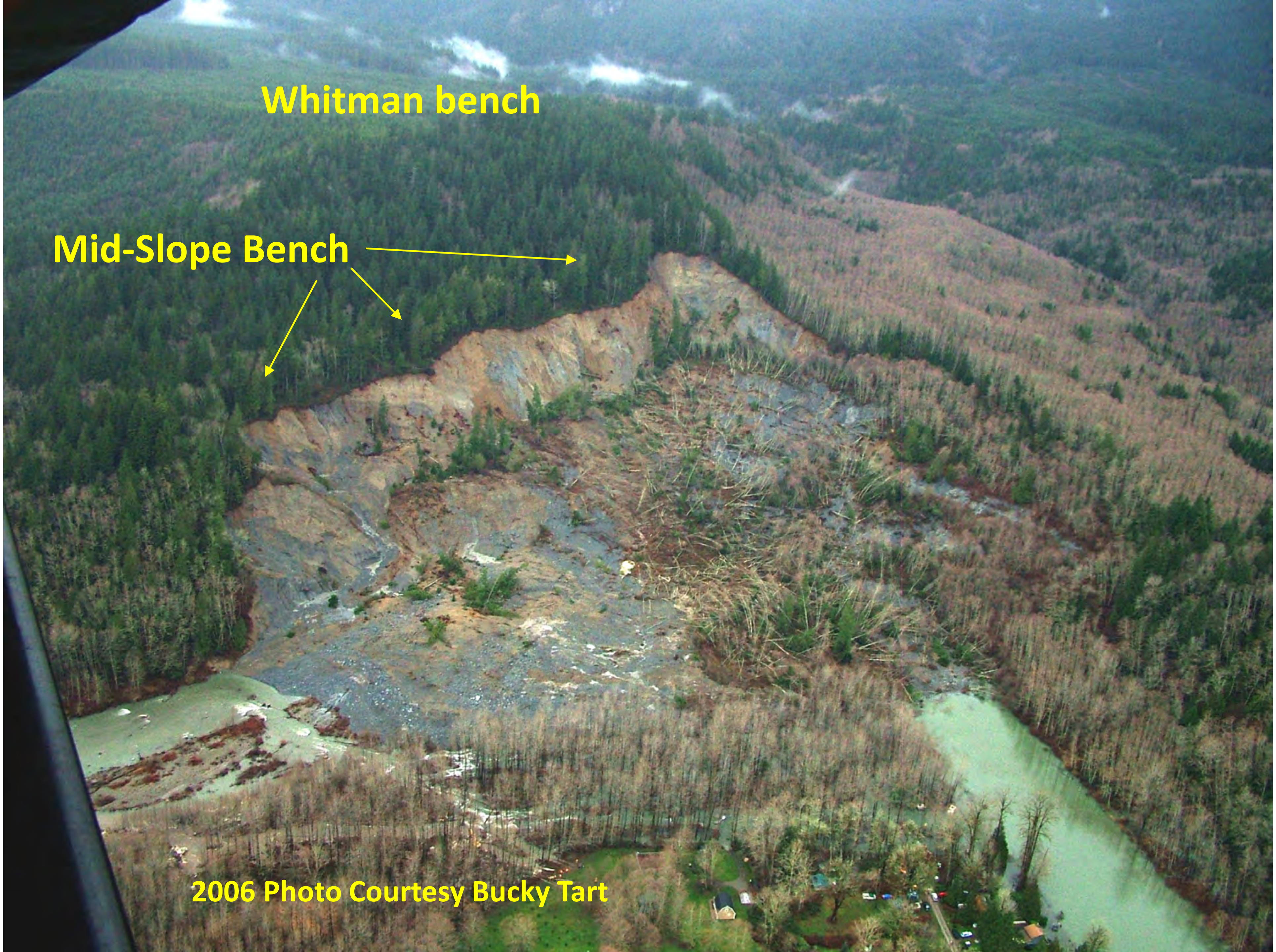


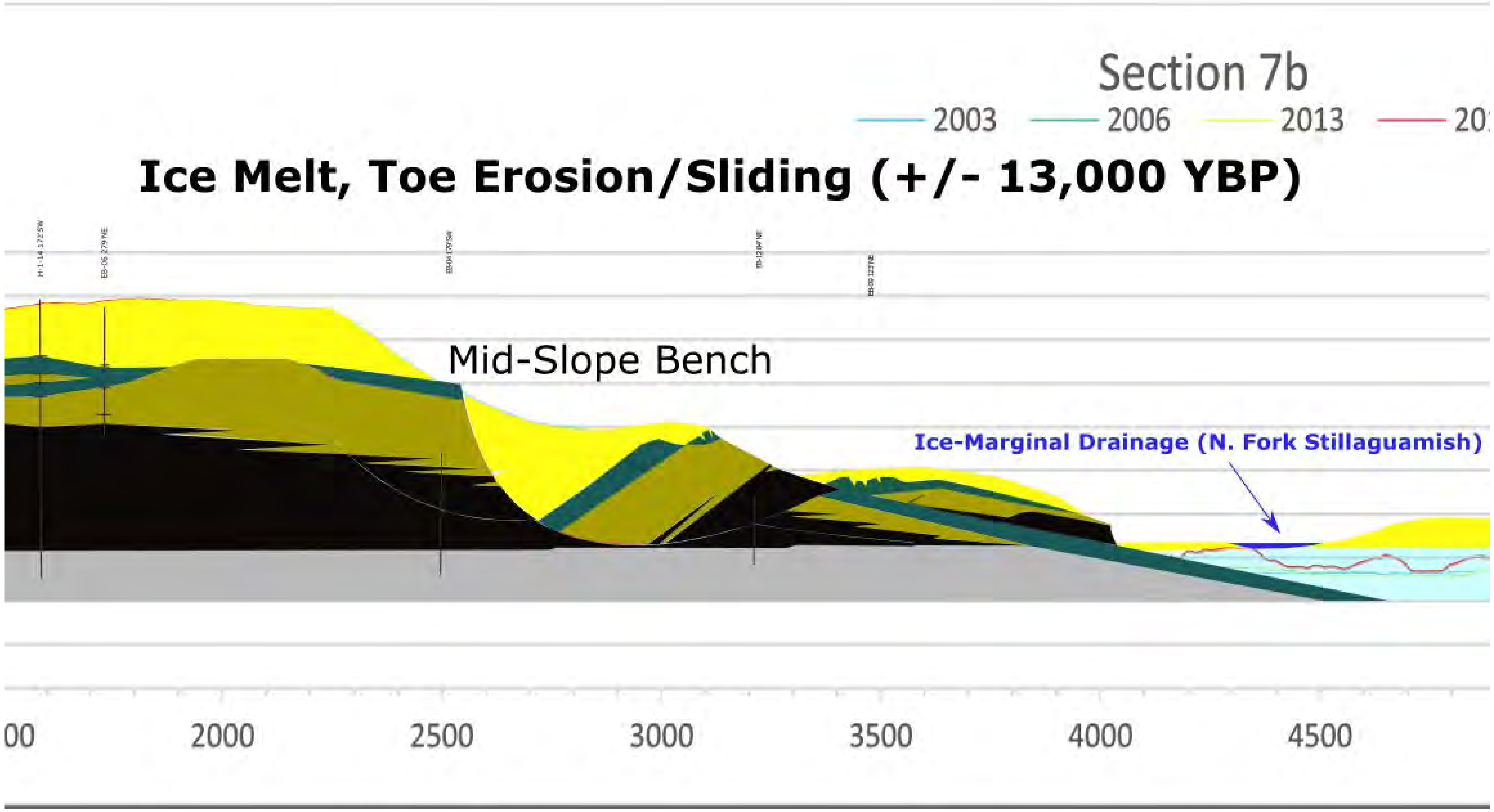
2013 LiDAR
Surface of Rupture
At base of Mid-Slope Bench
0 250 500 750 ft

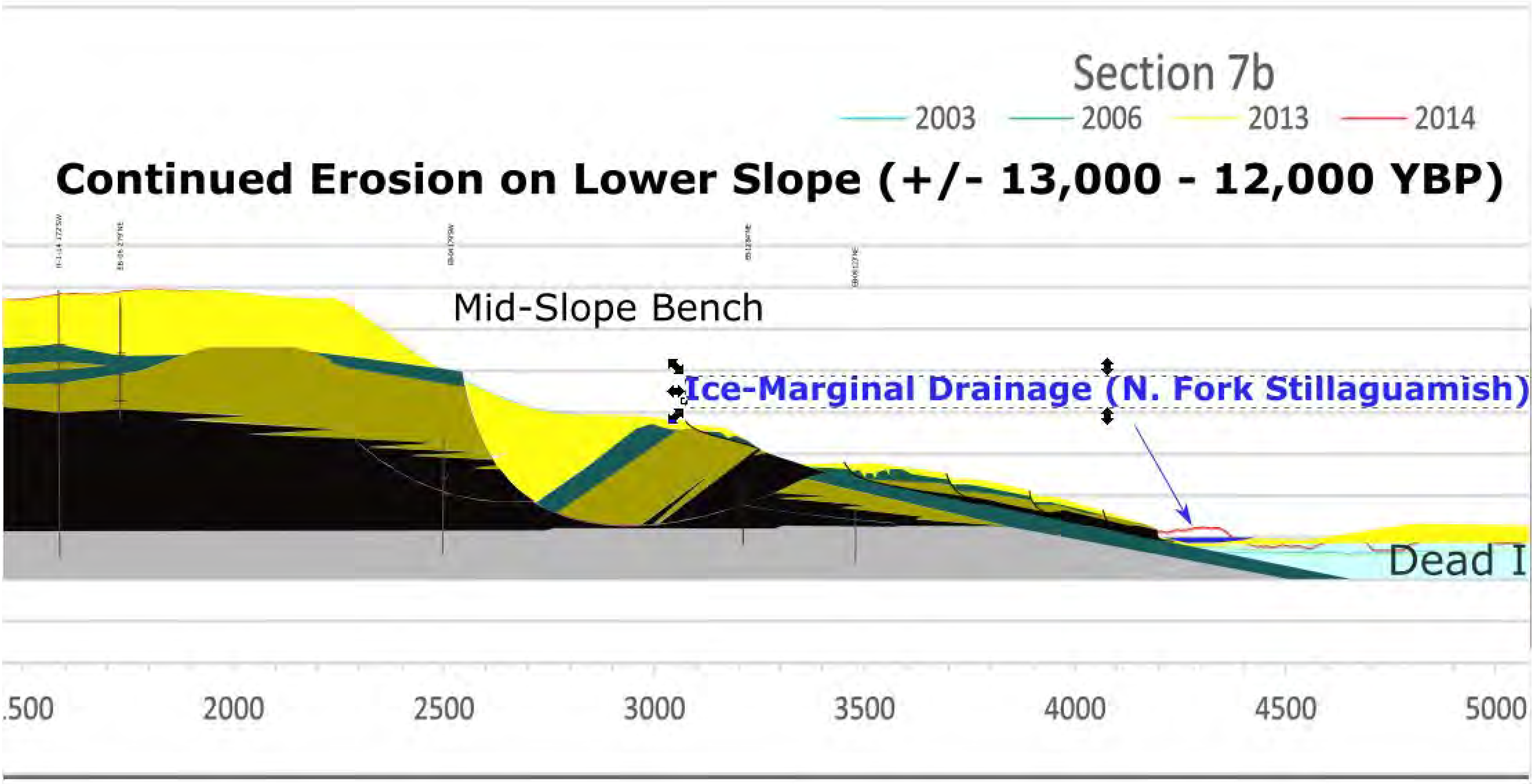


4/6/2014 LiDAR
2014 Surface of Rupture
Exposure in Gully
Surface of Rupture
At base of Mid-Slope Bench
0 250 500 750 ft

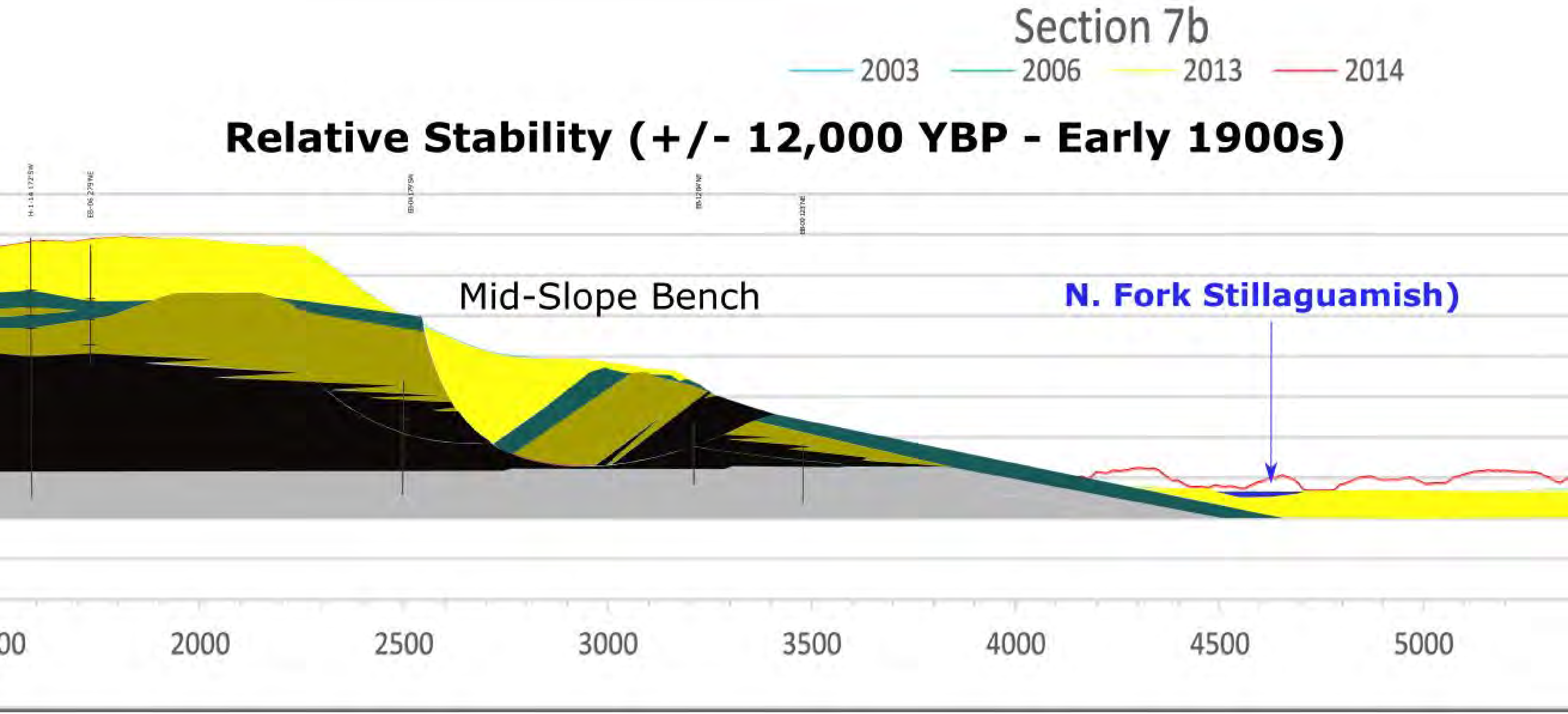

Surface of Rupture 2014 Failure
Fine-Grained Glacio-Lacustrine
Bear Lake Sand

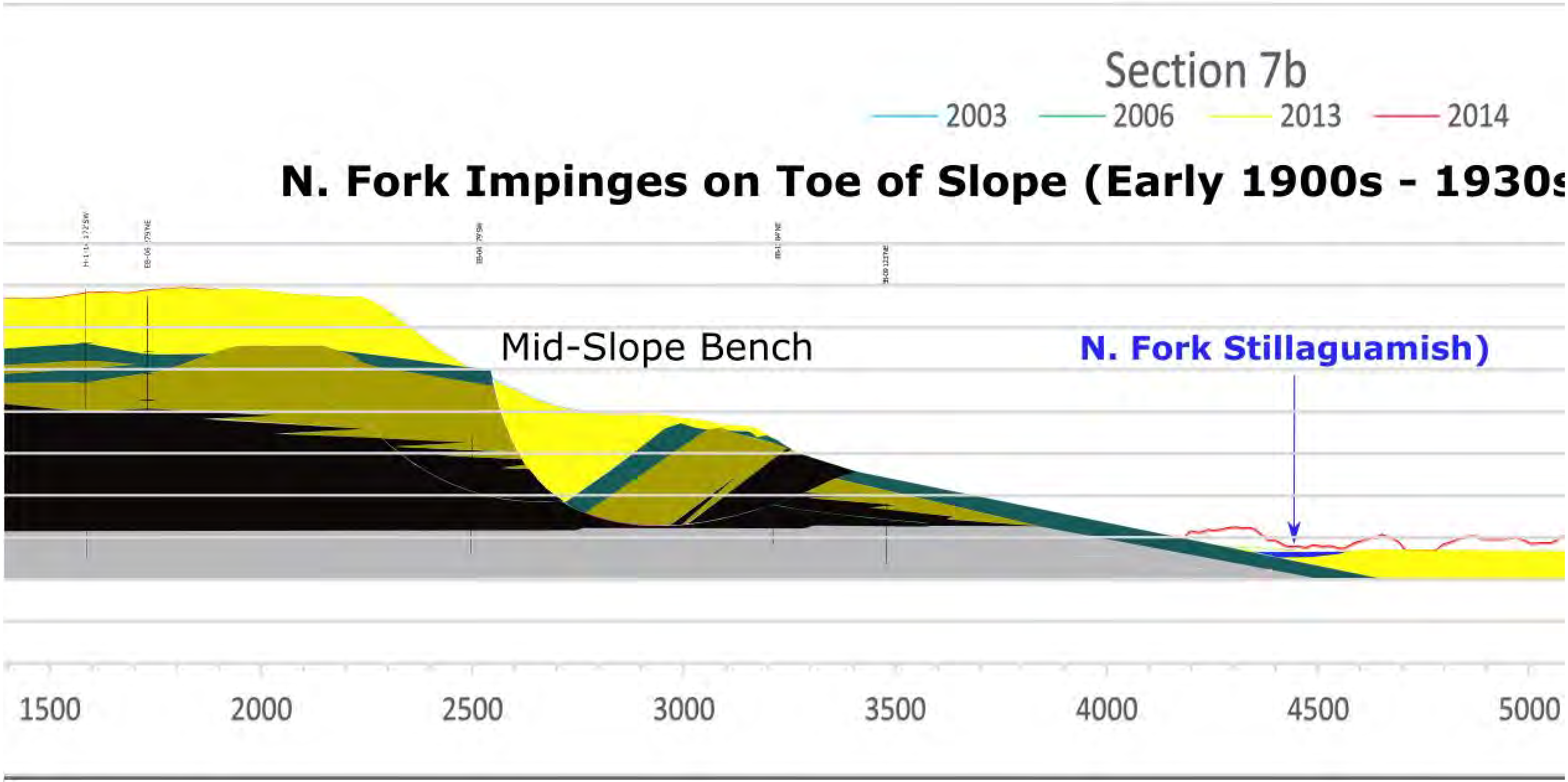

Whitman bench
Mid-Slope Bench
2006 Photo Courtesy Bucky Tart


Section 7b
2003
2006
2013
20
Ice Melt, Toe Erosion/Sliding (+/- 13,000 YBP)
Mid-Slope Bench
Ice-Marginal Drainage (N. Fork Stillaguamish)
00
2000
2500
3000
3500
4000
4500



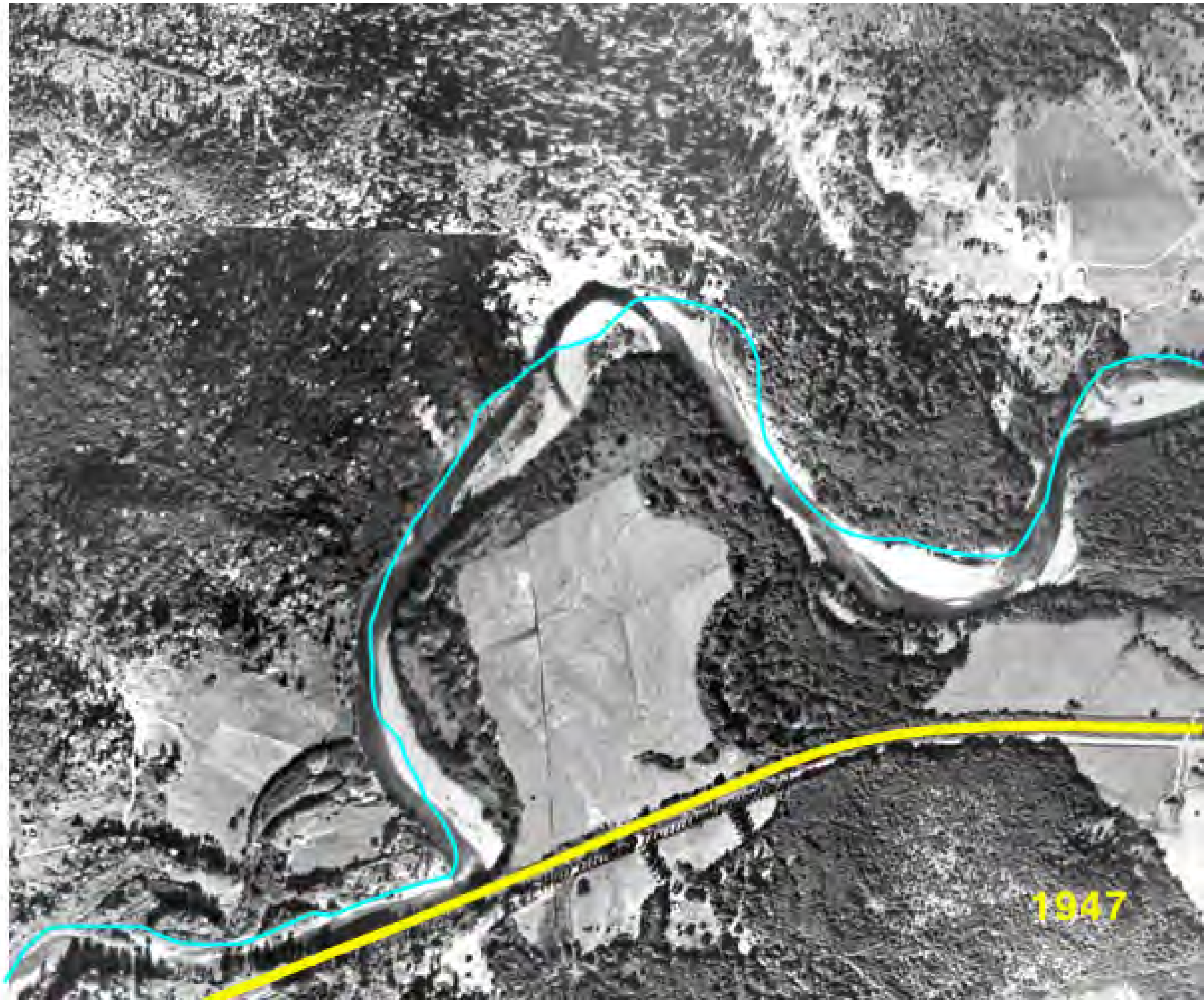
Section 7b
2003
2006
2013
2014
Continued Erosion on Lower Slope (+/- 13,000 - 12,000 YBP)
Mid-Slope Bench
Ice-Marginal Drainage (N. Fork Stillaguamish)
Dead I
.500
2000
2500
3000
3500
4000
4500
5000

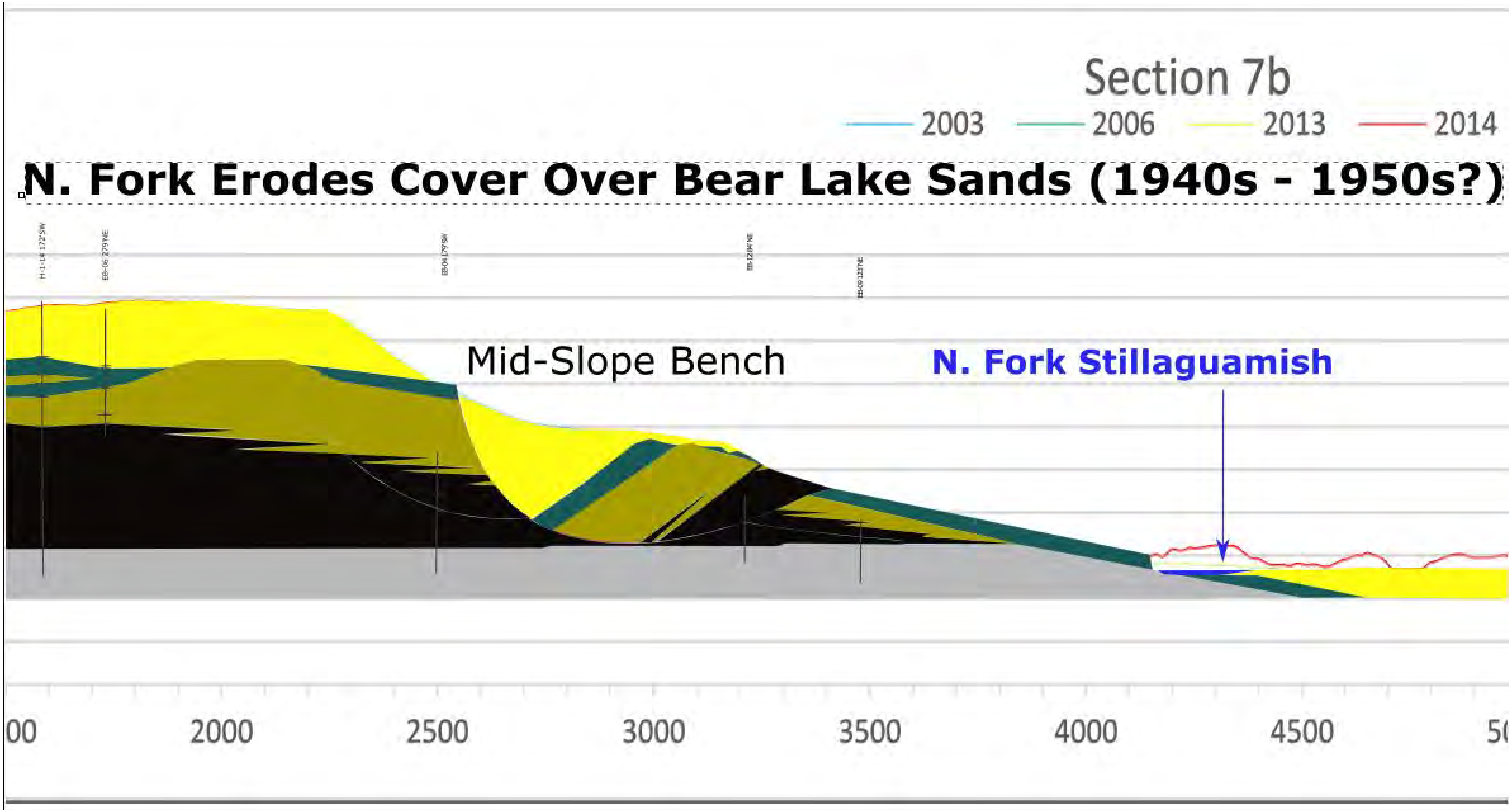

Section 7b
2003
2006
2013
2014
Relative Stability (+/- 12,000 YBP - Early 1900s)
Mid-Slope Bench
N. Fork Stillaguamish)
00
2000
2500
3000
3500
4000
4500
5000



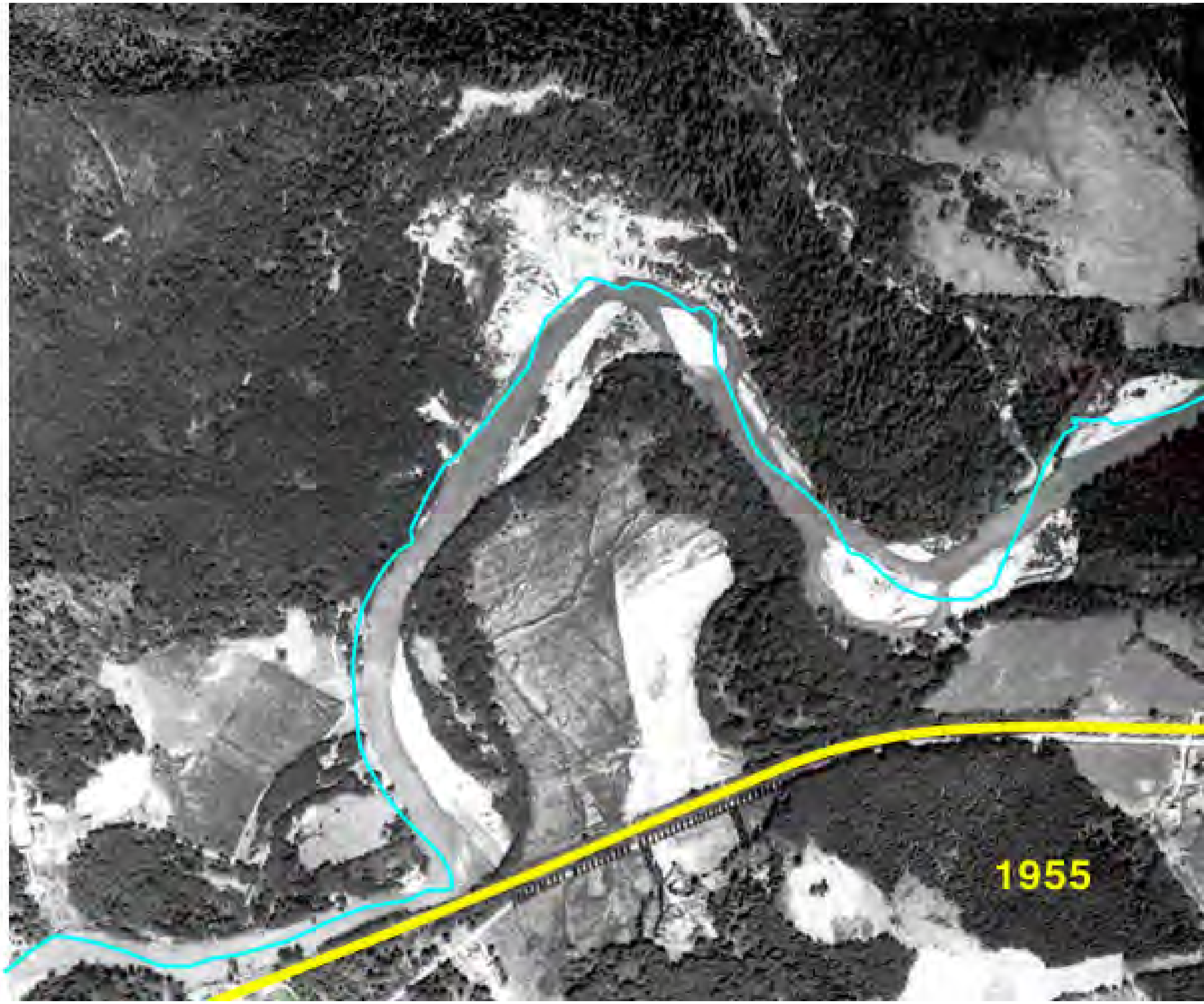
Section 7b
2003
2006
2013
2014
N. Fork Impinges on Toe of Slope (Early 1900s - 1930s
Mid-Slope Bench
N. Fork Stillaguamish)
1500
2000
2500
3000
3500
4000
4500
5000

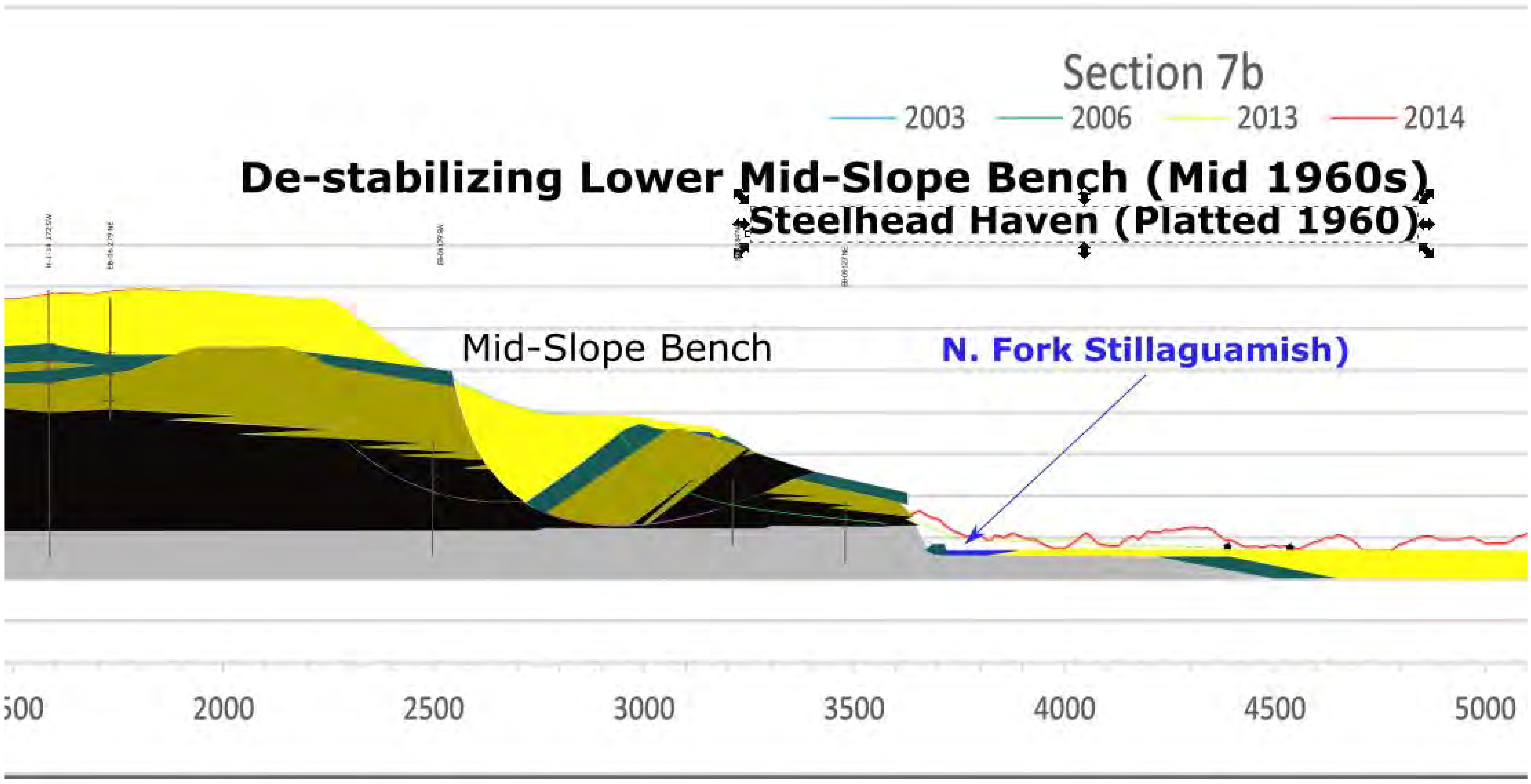

1933


1947

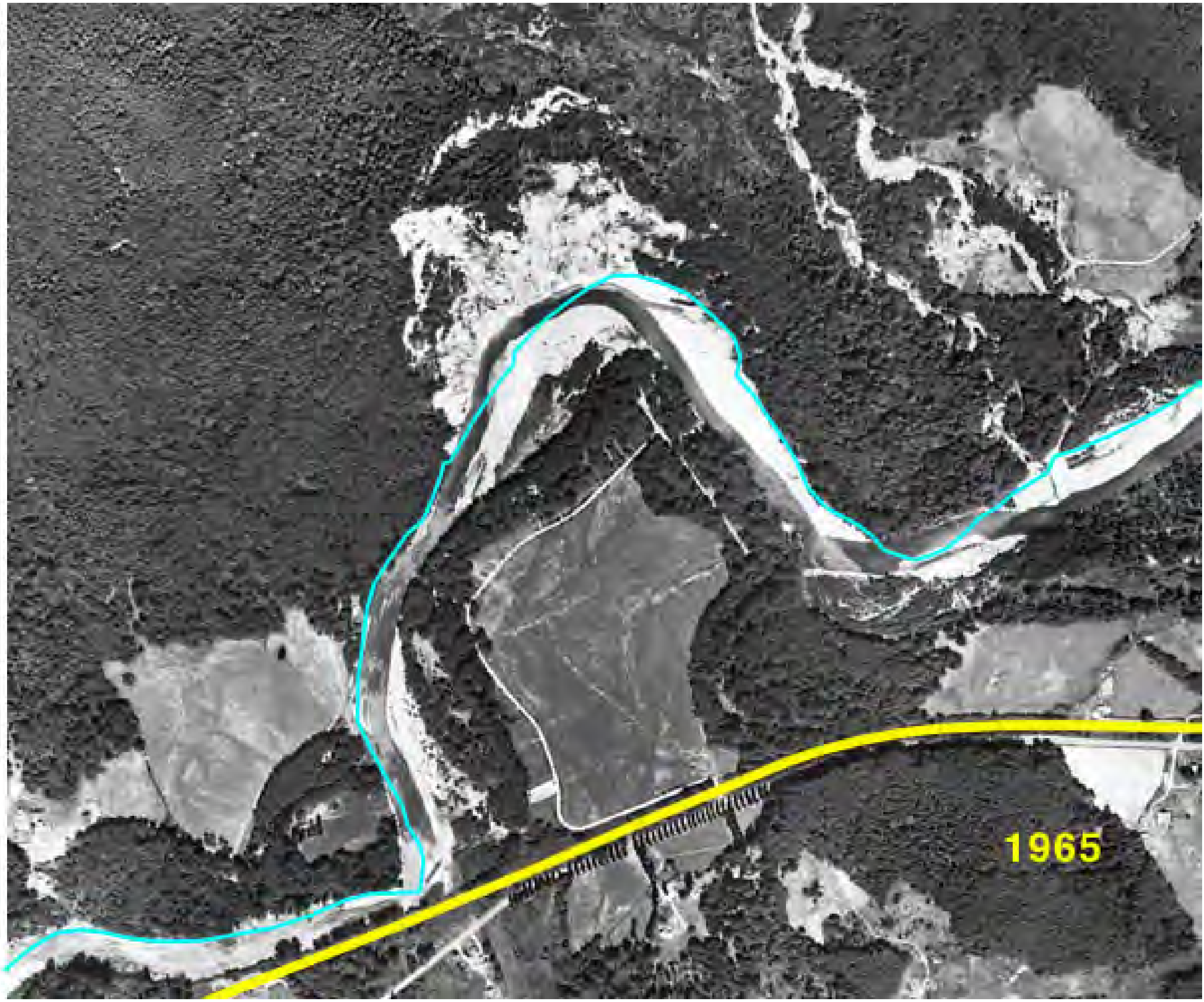

Section 7b
2003
2006
2013
2014
N. Fork Erodes Cover Over Bear Lake Sands (1940s - 1950s?)
Mid-Slope Bench
N. Fork Stillaguamish
00
2000
2500
3000
3500
4000
4500
5(

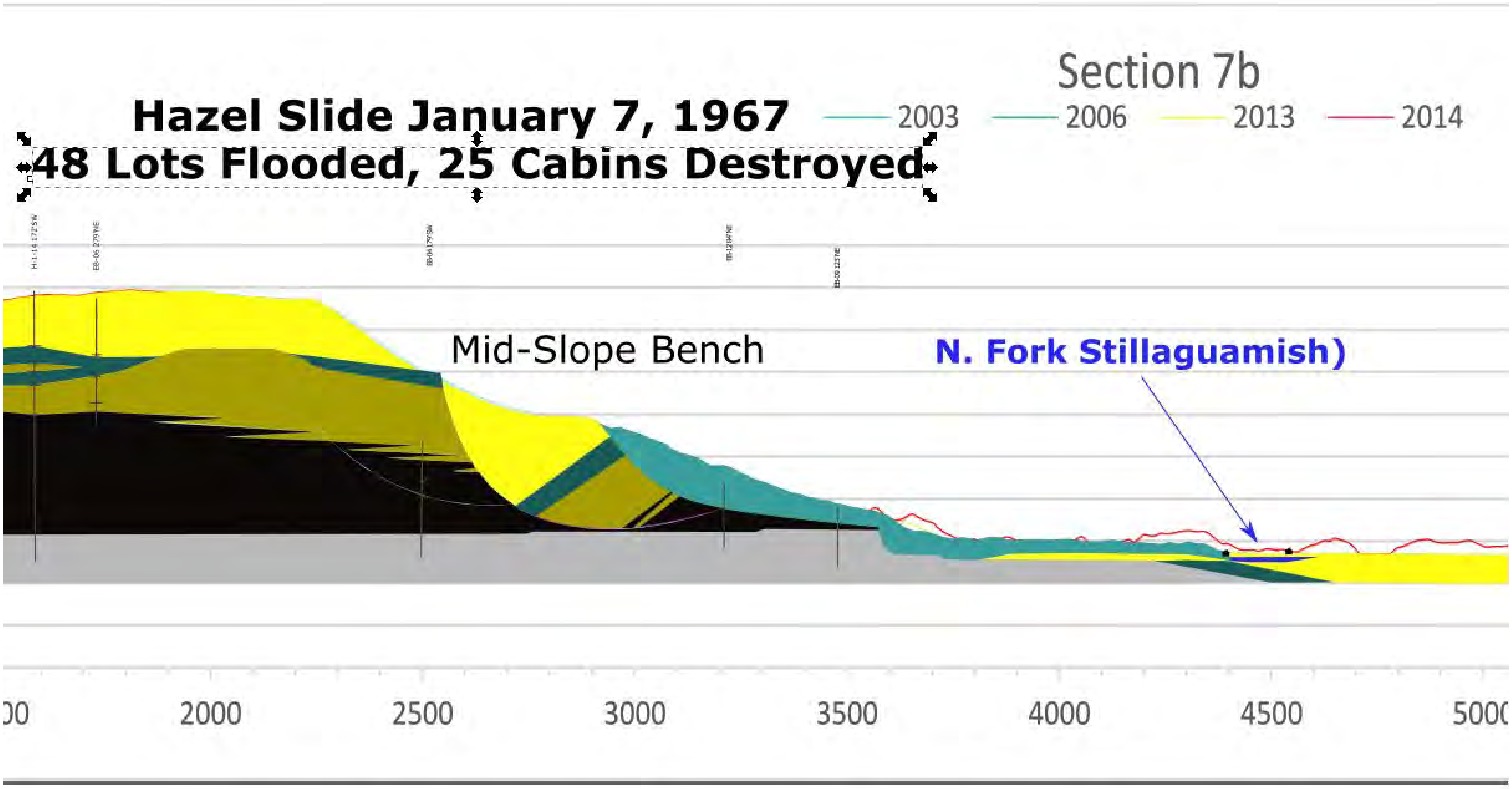

1947


1955


Section 7b
2003
2006
2013
2014
De-stabilizing Lower Mid-Slope Bench (Mid 1960s)
Steelhead Haven (Platted 1960)
Mid-Slope Bench
N. Fork Stillaguamish)
500
2000
2500
3000
3500
4000
4500
5000

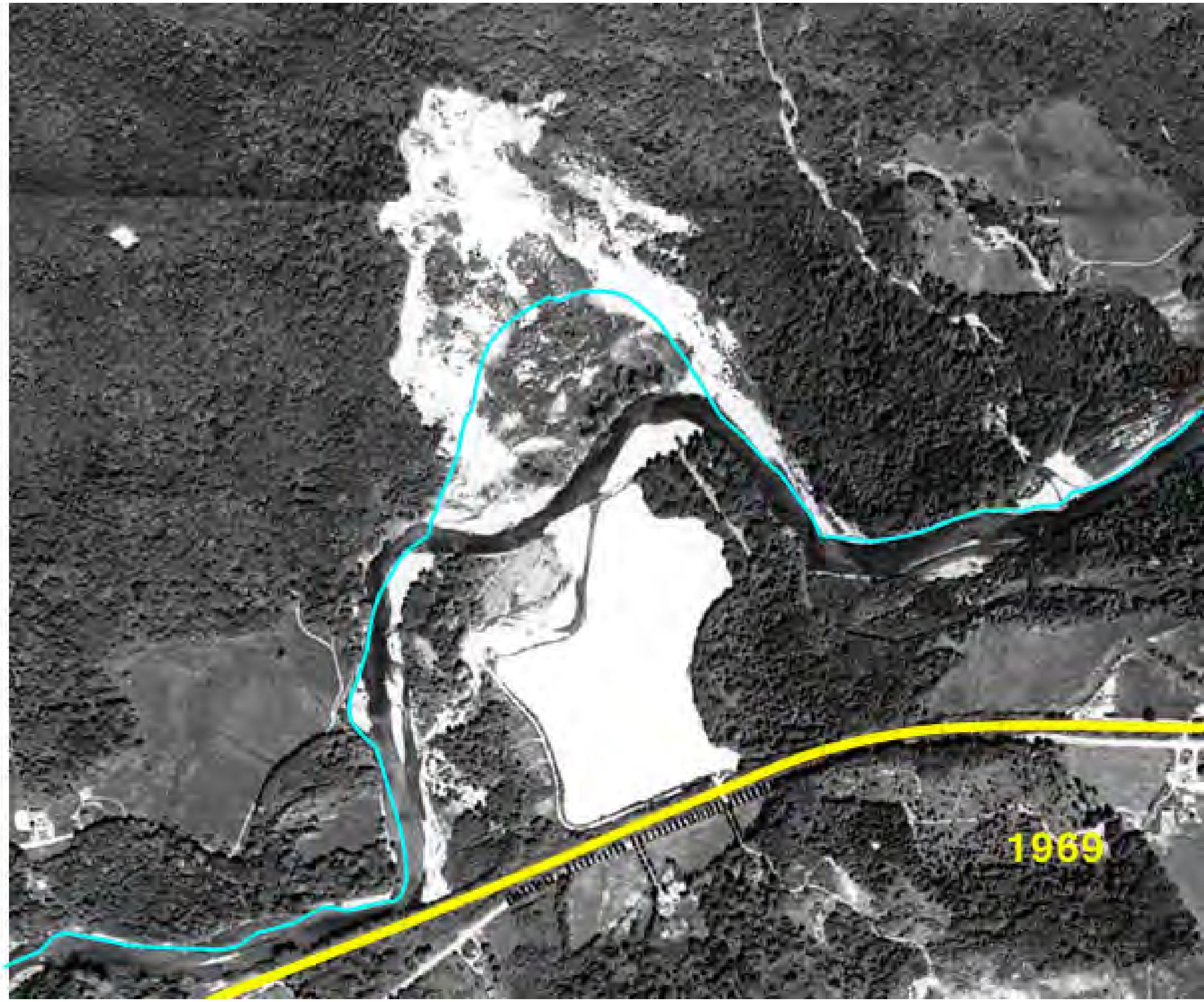

1955

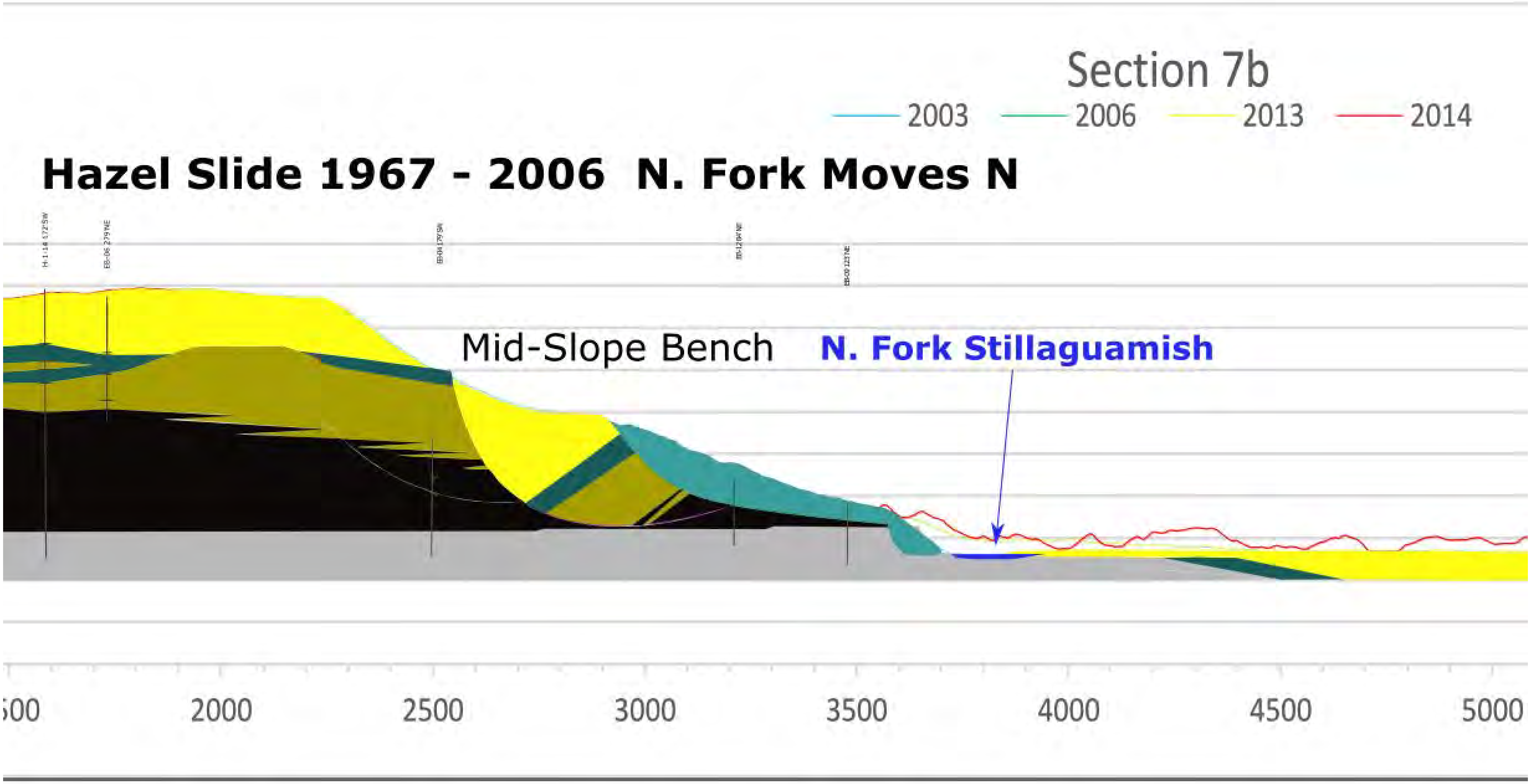

1965

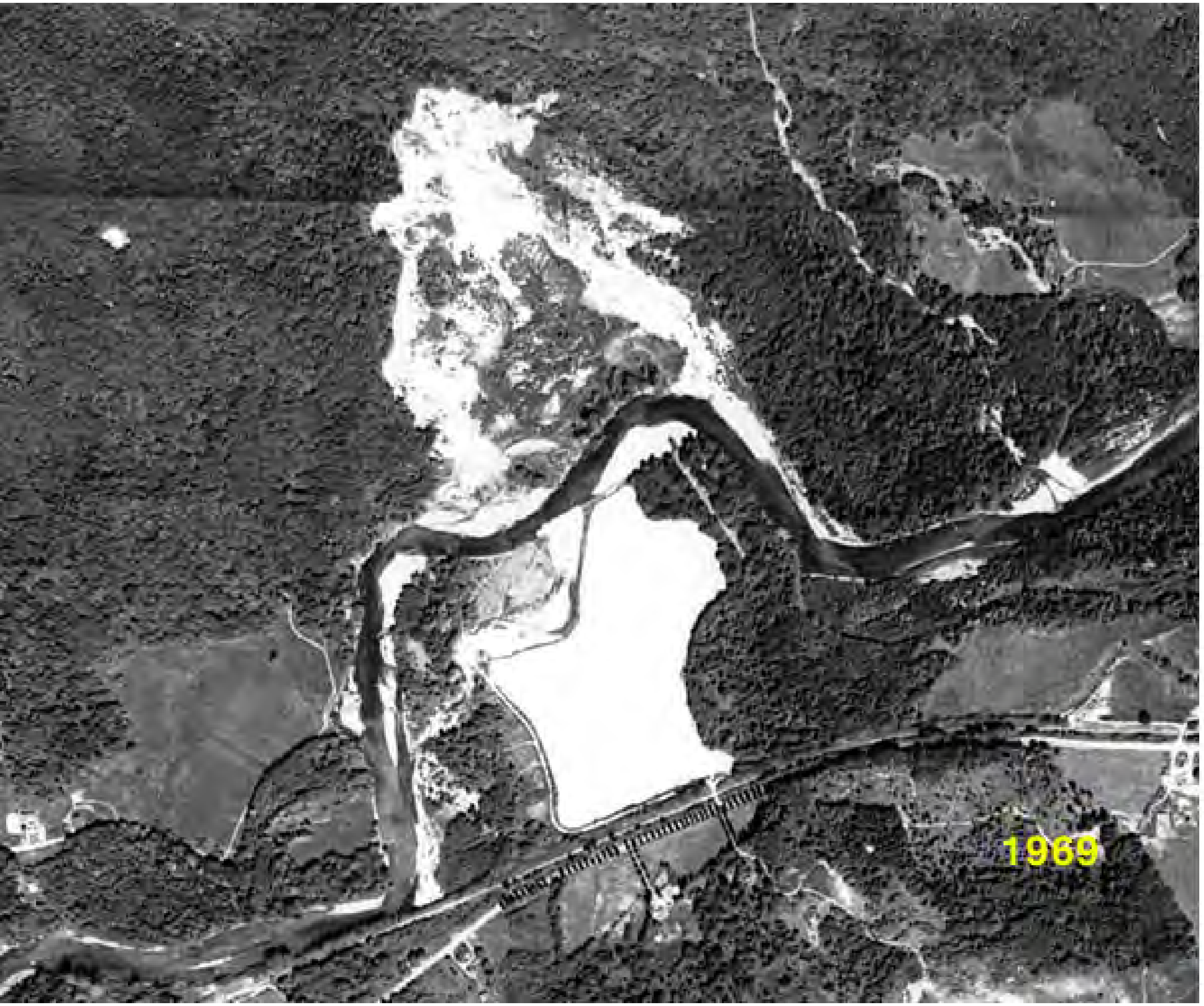


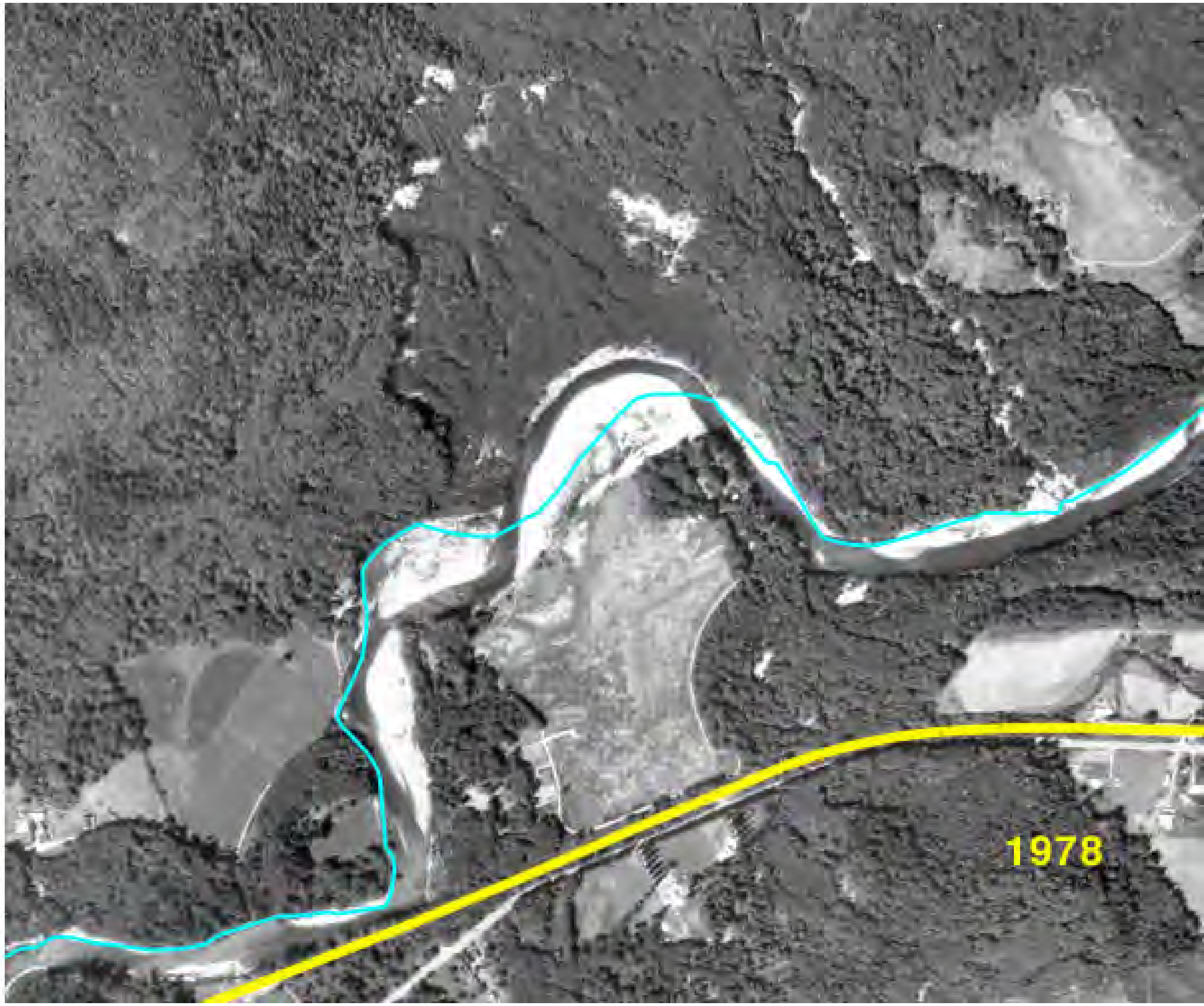
Section 7b
2003
2006
2013
2014
Hazel Slide January 7, 1967
48 Lots Flooded, 25 Cabins Destroyed
Mid-Slope Bench
N. Fork Stillaguamish)
00
2000
2500
3000
3500
4000
4500
500

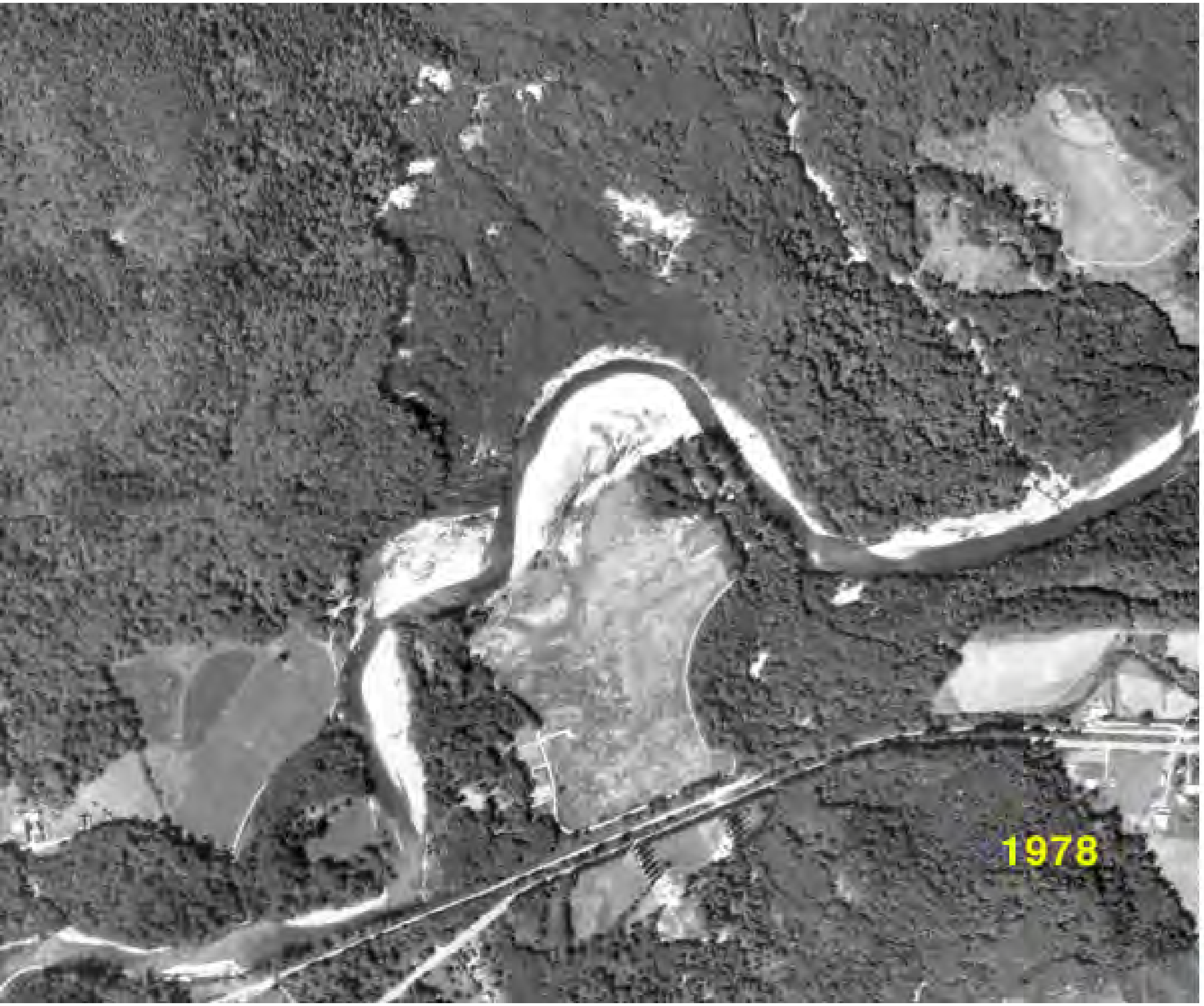
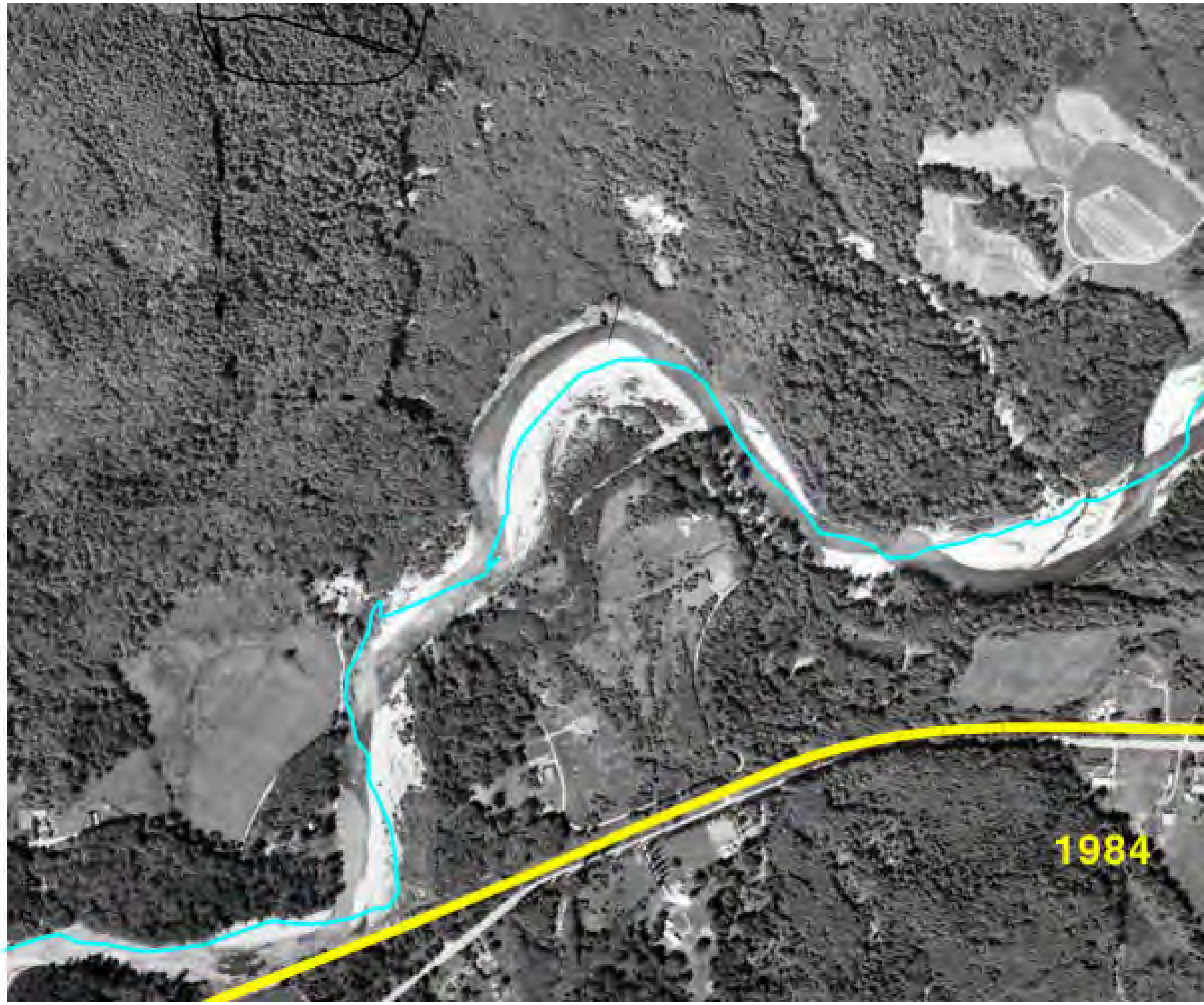

1965


1969

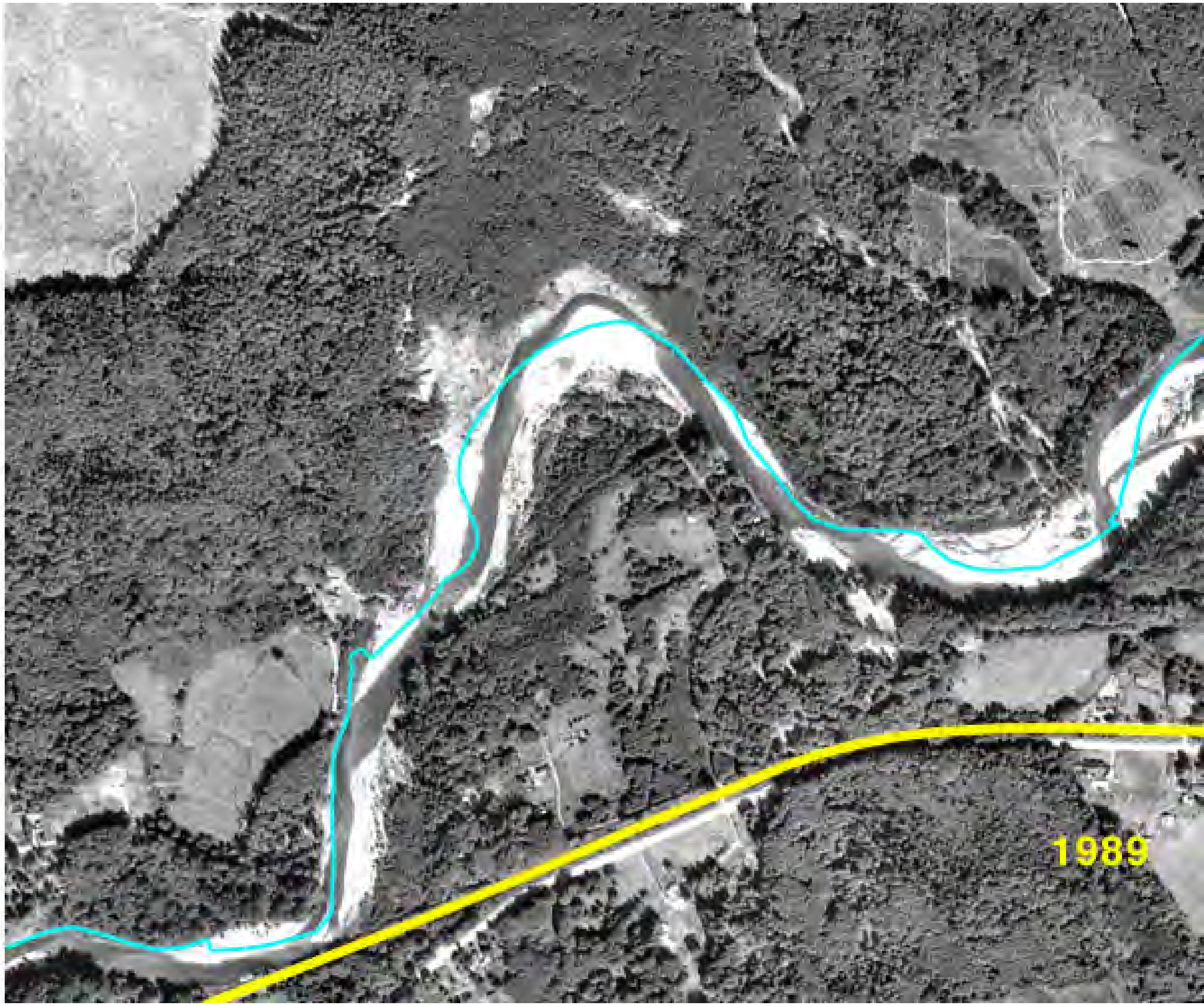

Section 7b
2003
2006
2013
2014
Hazel Slide 1967 - 2006 N. Fork Moves N
Mid-Slope Bench
N. Fork Stillaguamish
500
2000
2500
3000
3500
4000
4500
5000

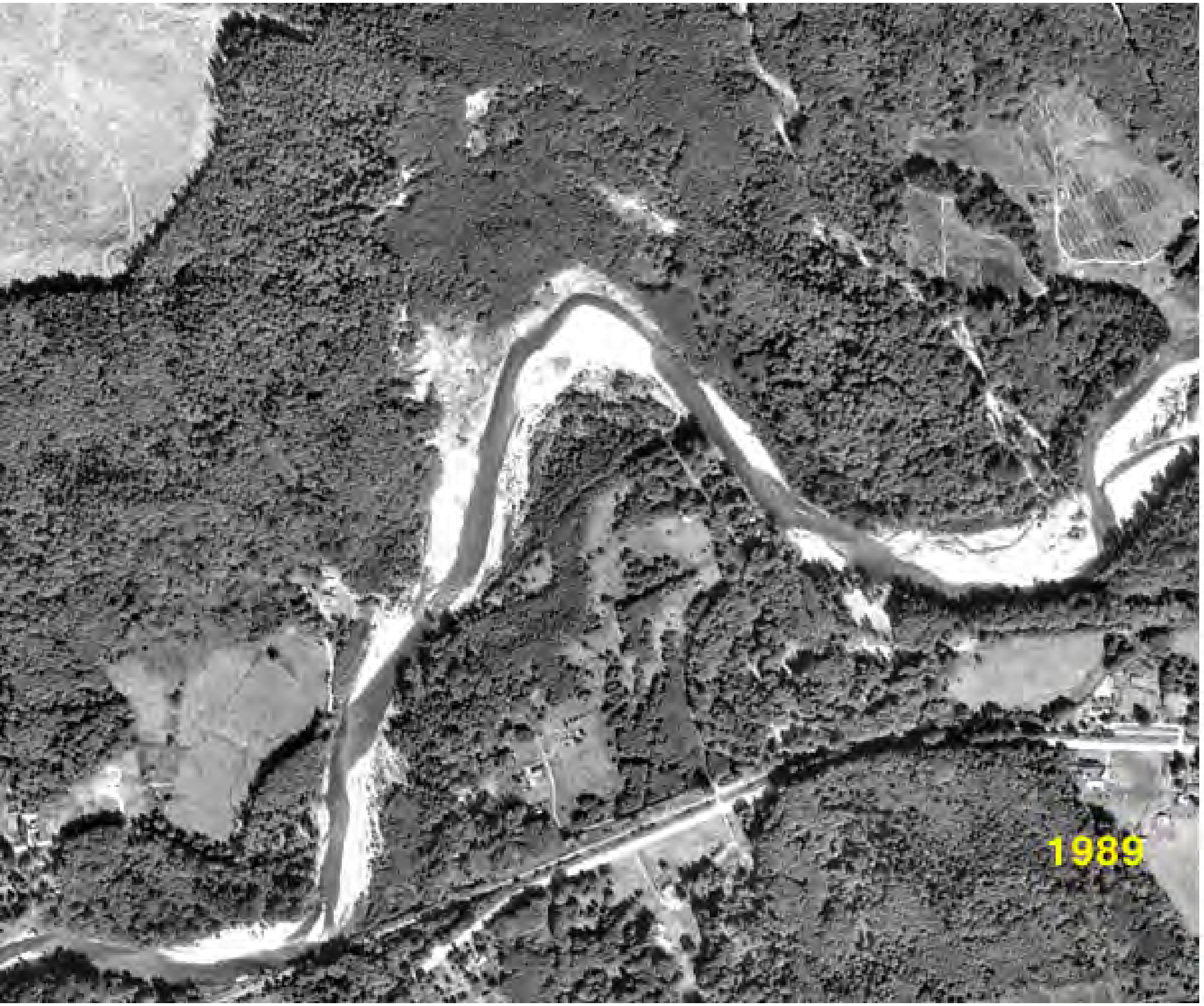

1969


1978


1978

1984

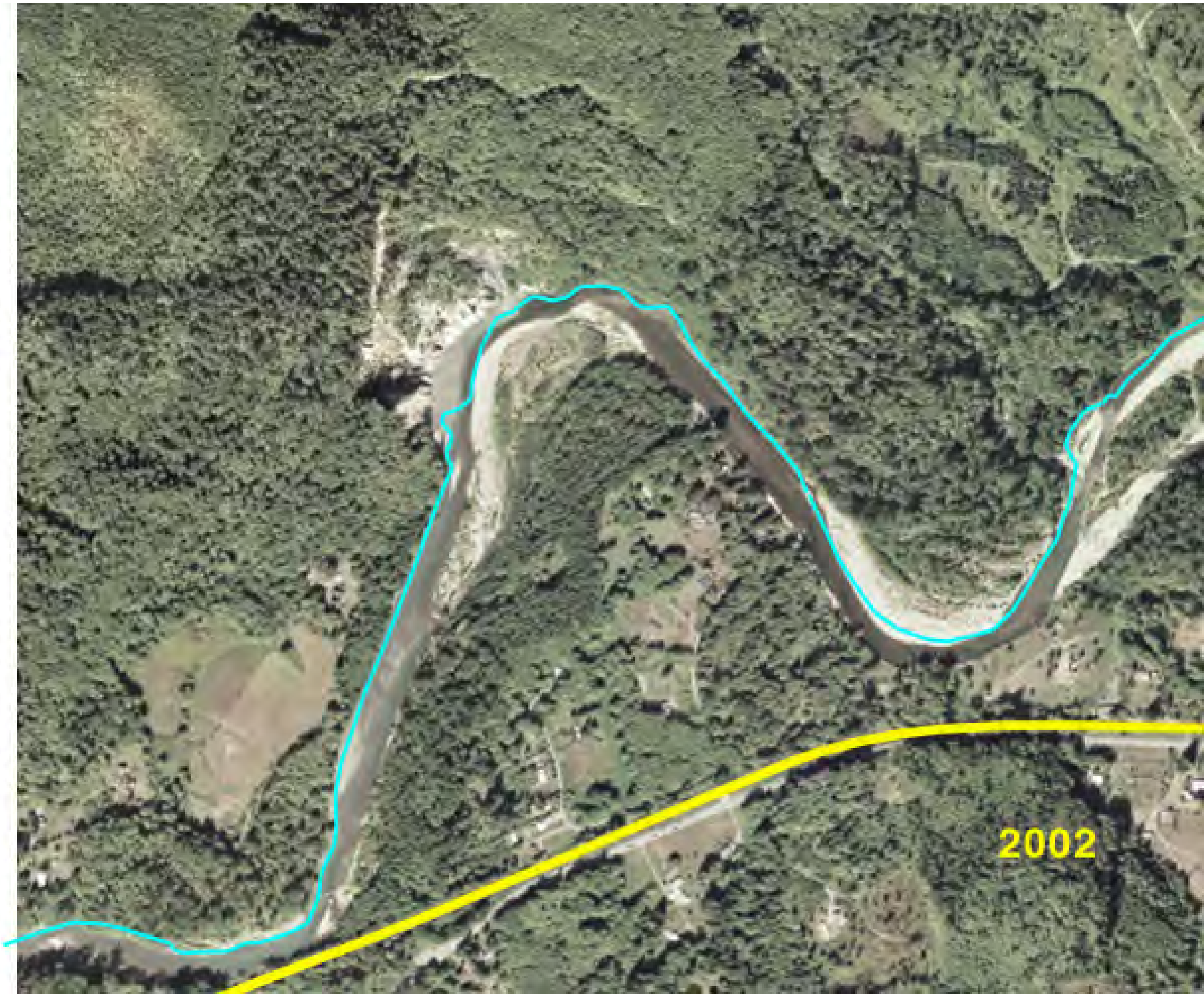

1984


1989

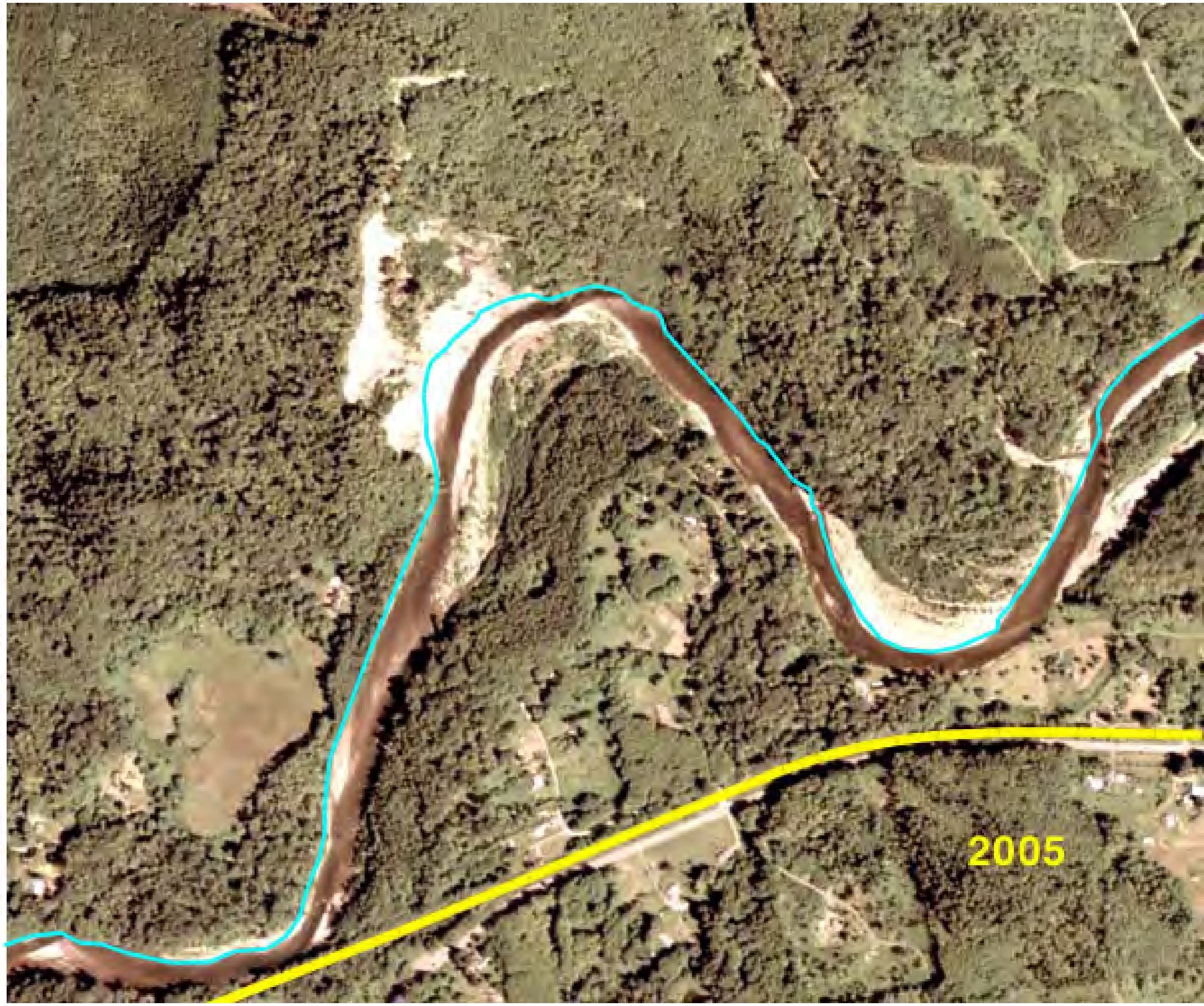

1989


1998


1998

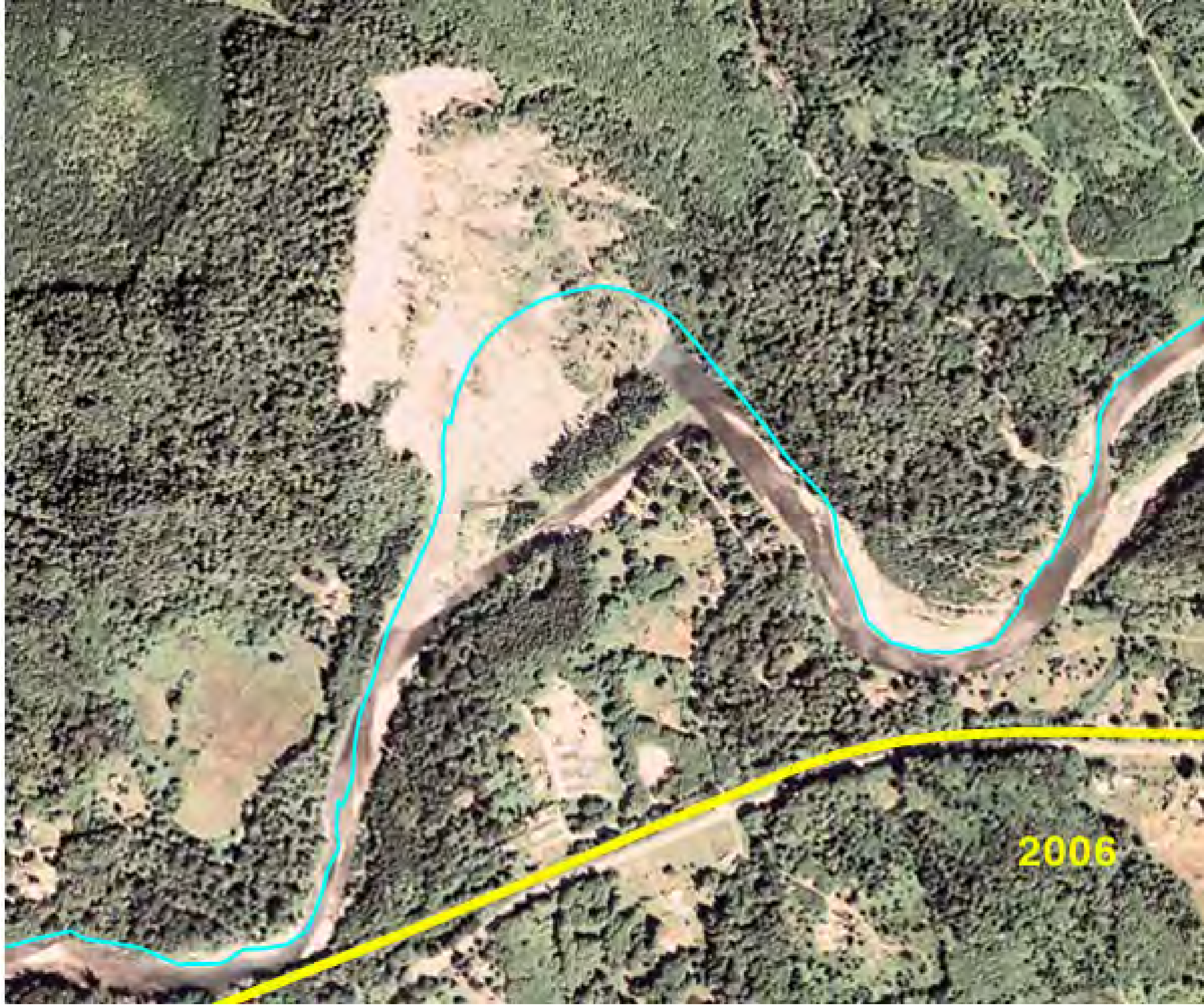

2002

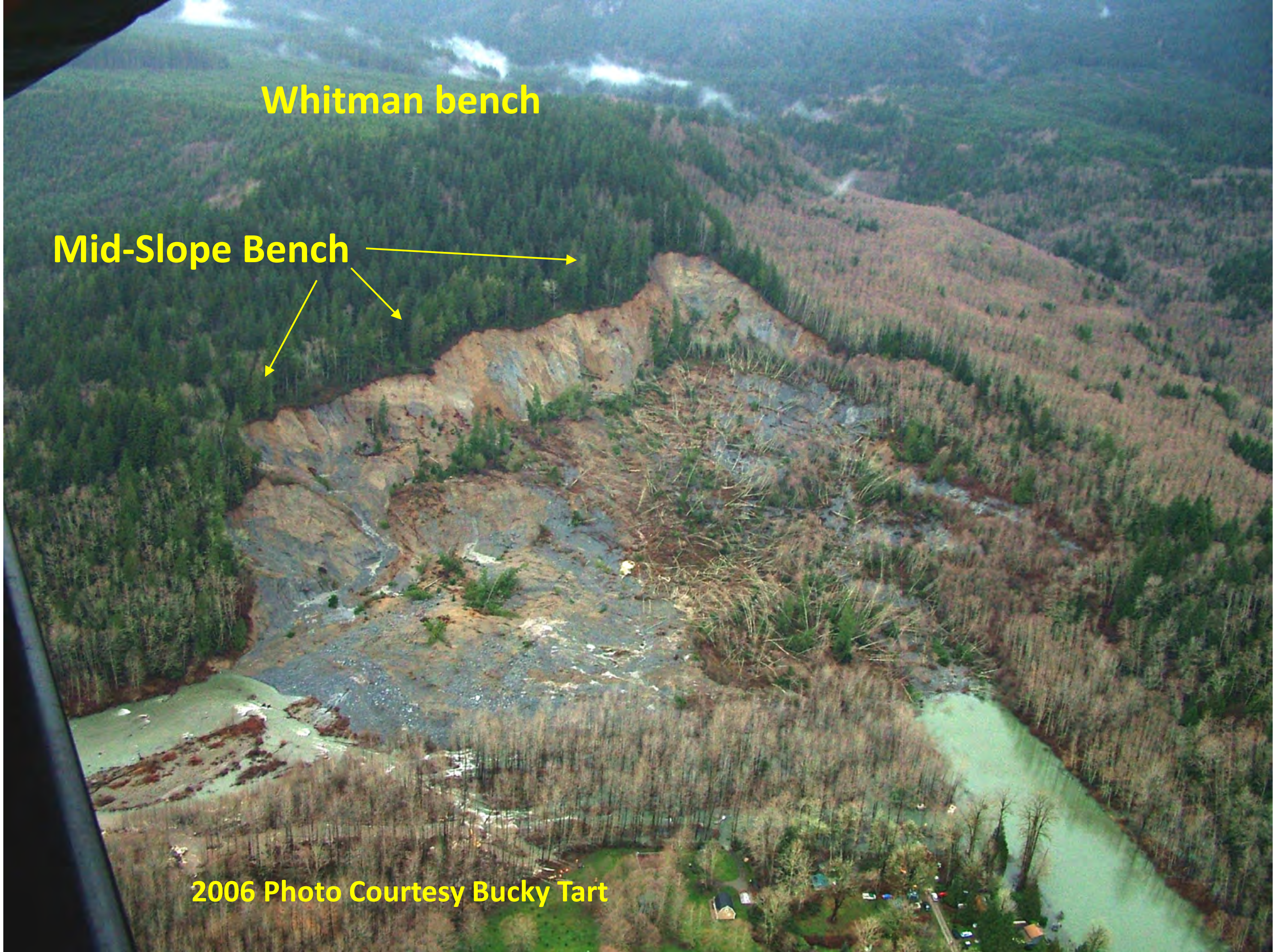

2002

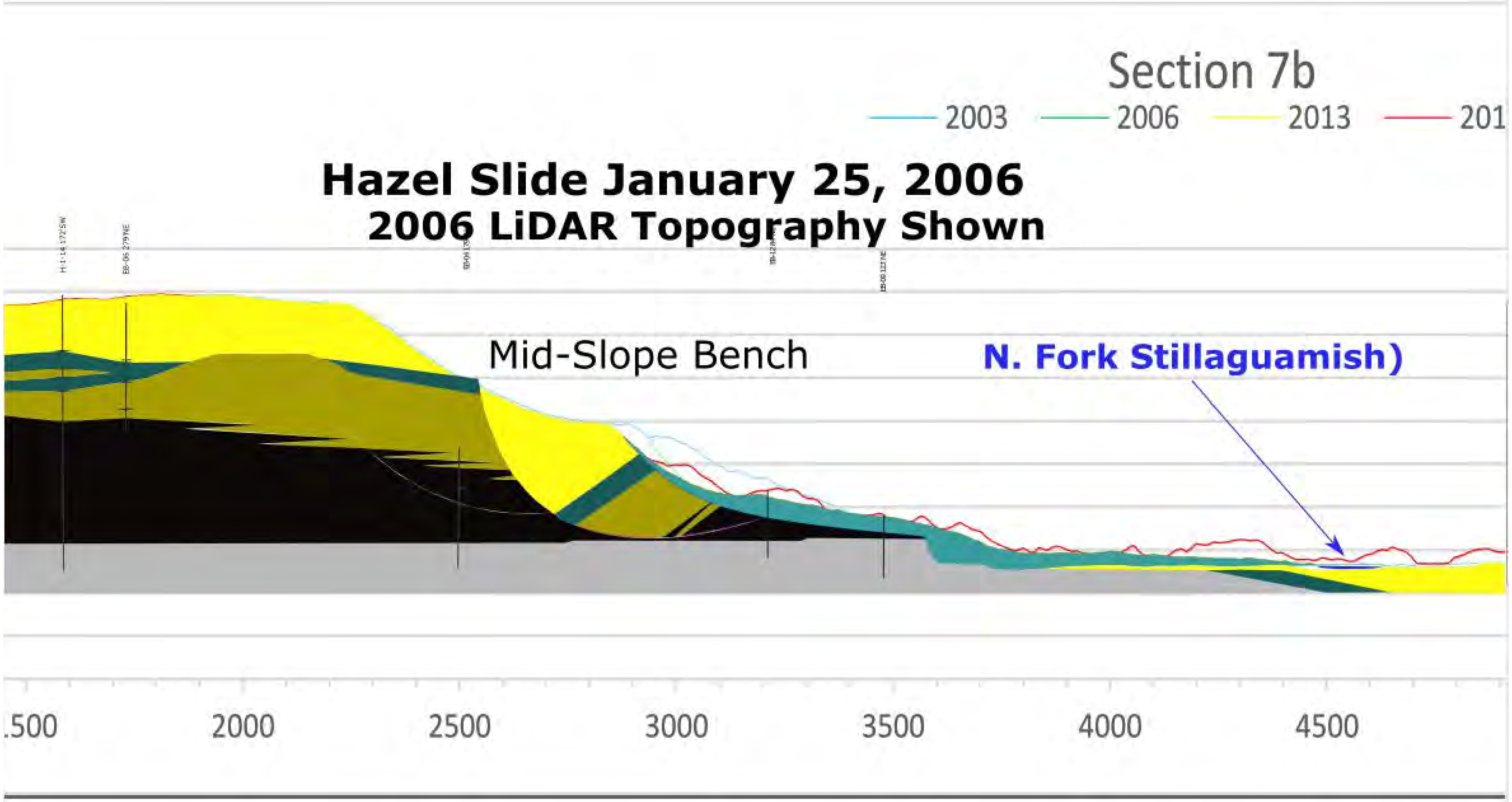

2005

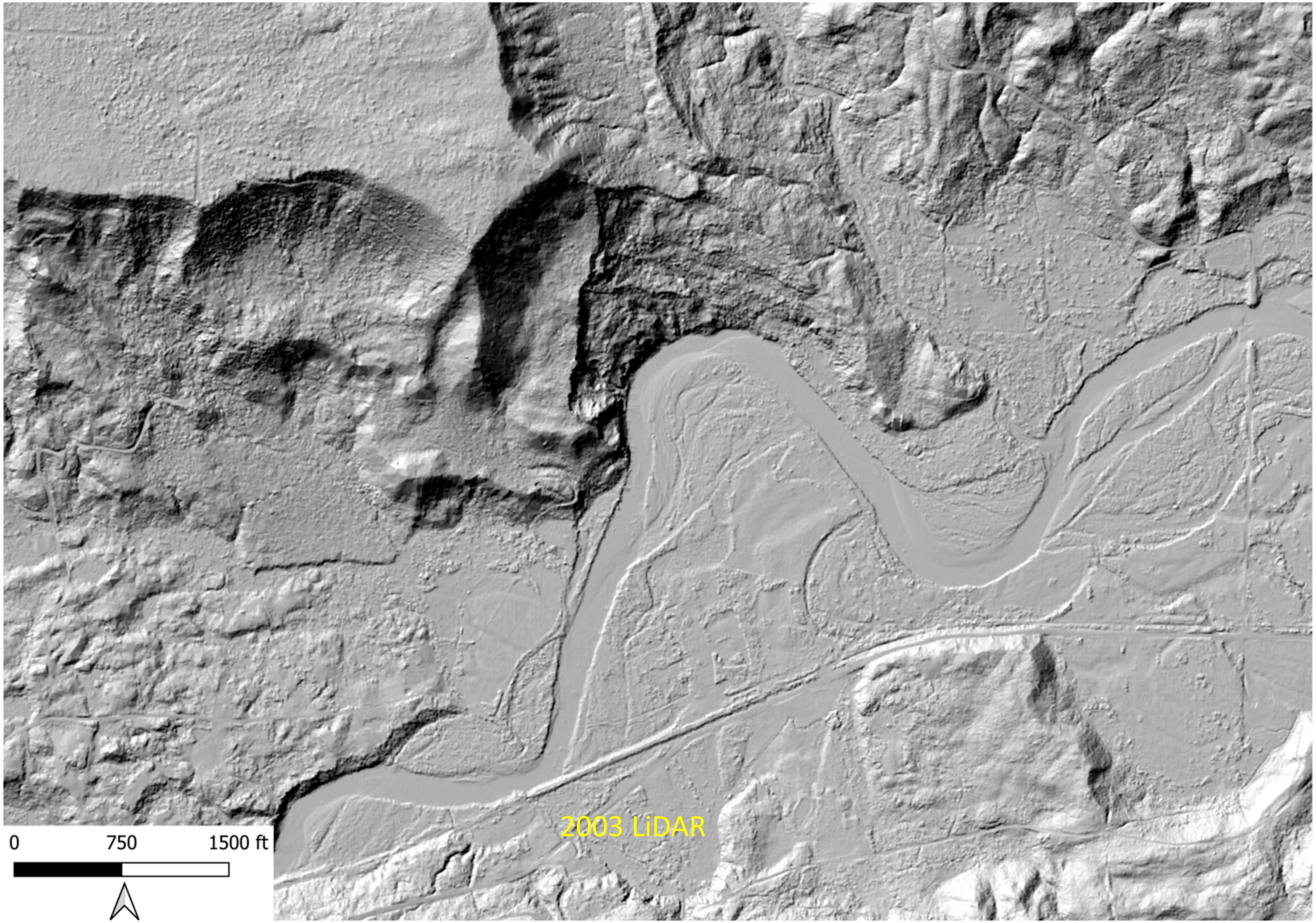

Whitman Bench
Mid-Slope Bench
Surface of Rupture
Bear Lake Sand
2003 Photo Courtesy of Bucky Tart

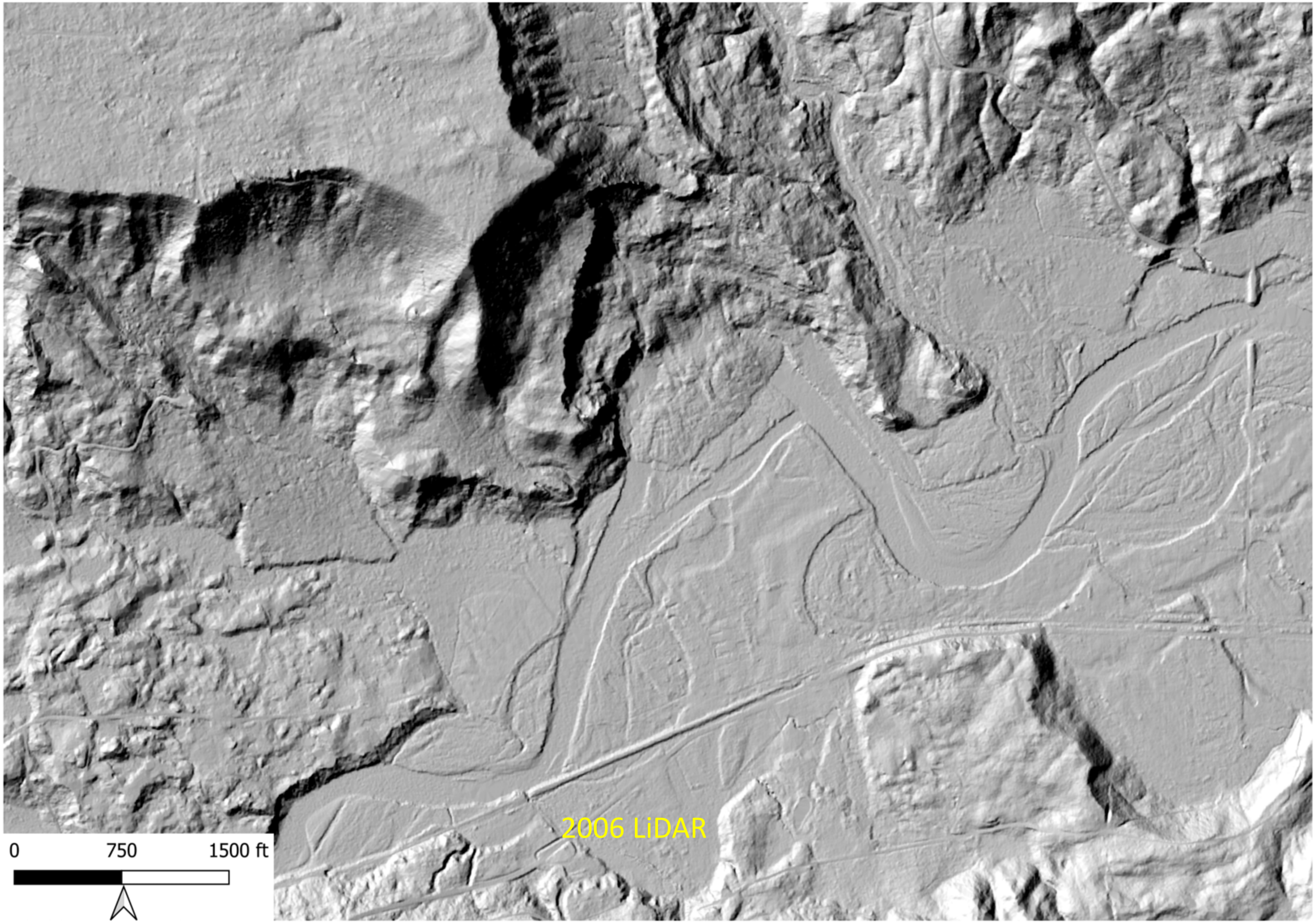

2005


2006

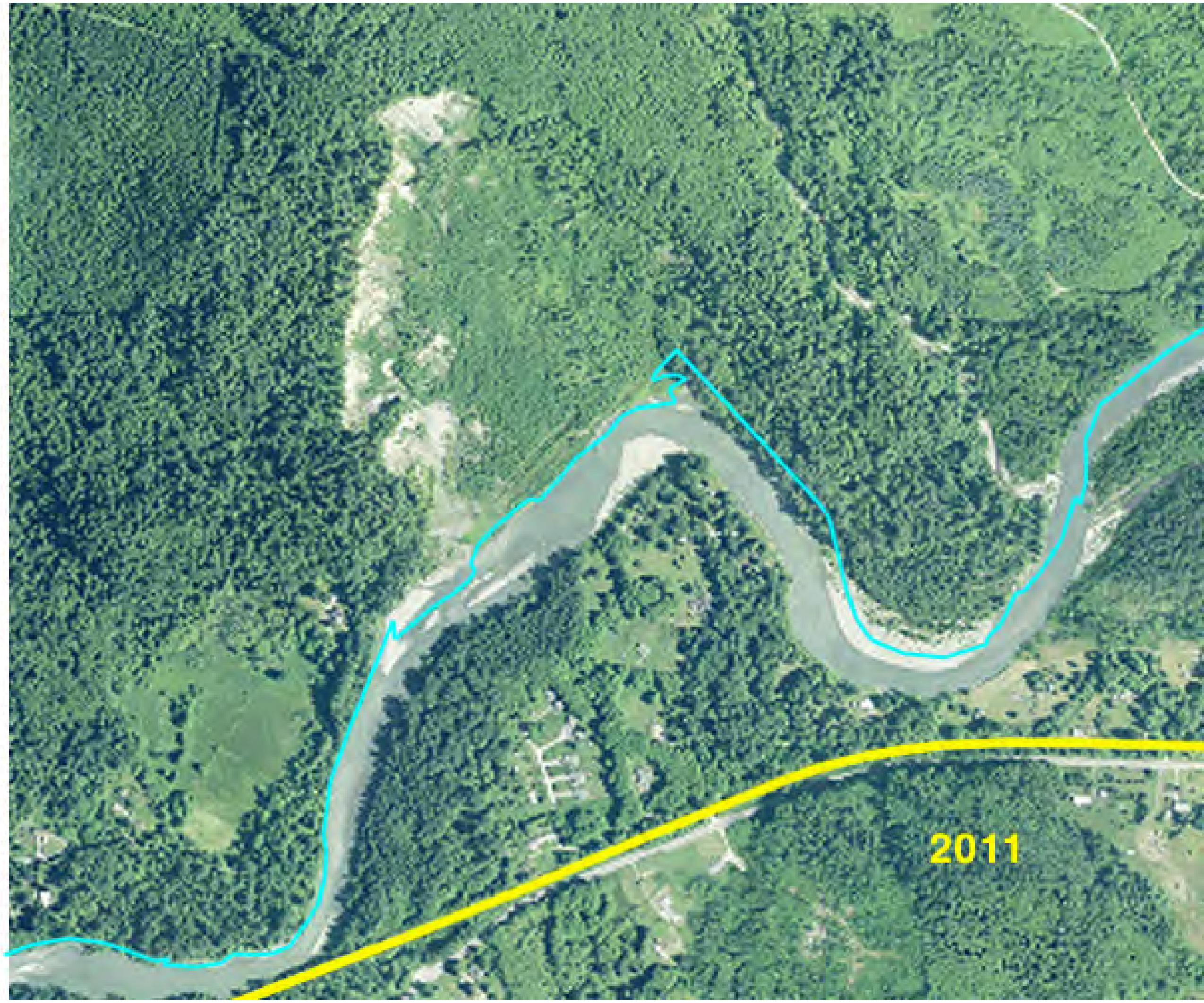

Whitman bench
Mid-Slope Bench
2006 Photo Courtesy Bucky Tart

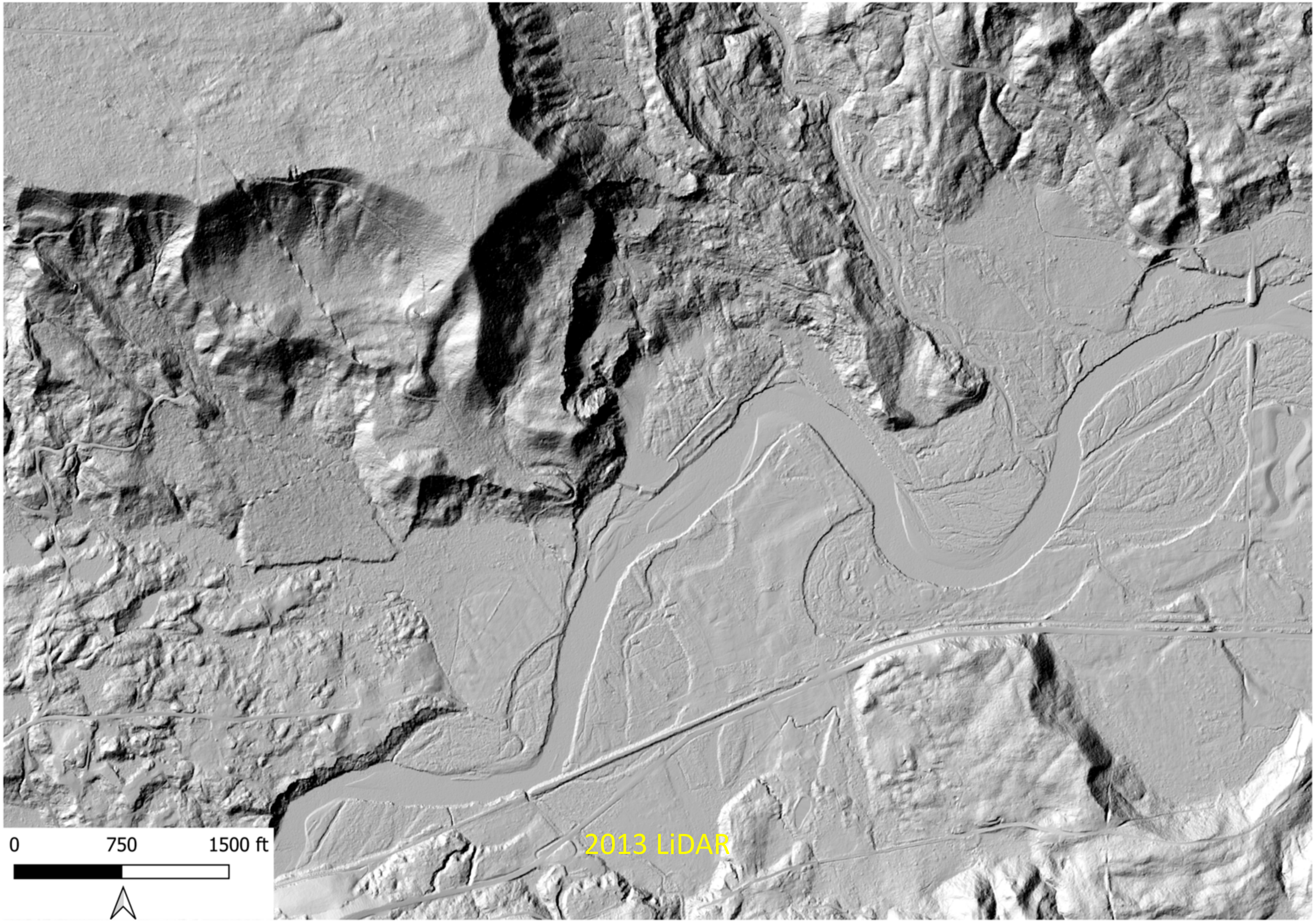

Section 7b
2003
2006
2013
201
Hazel Slide January 25, 2006
2006 LiDAR Topography Shown
Mid-Slope Bench
N. Fork Stillaguamish)
.500
2000
2500
3000
3500
4000
4500

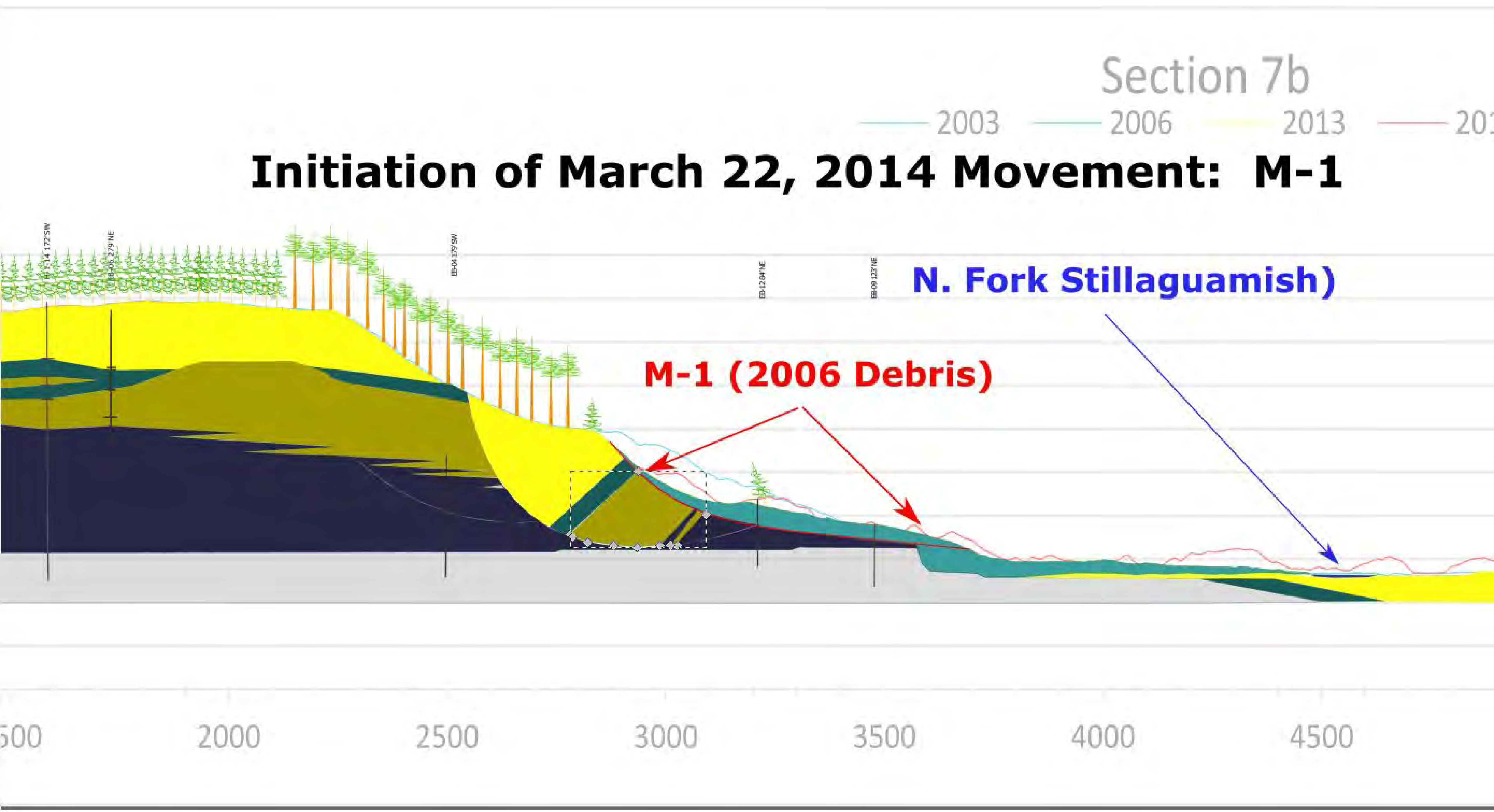

0
750
1500 ft
2003 LiDAR

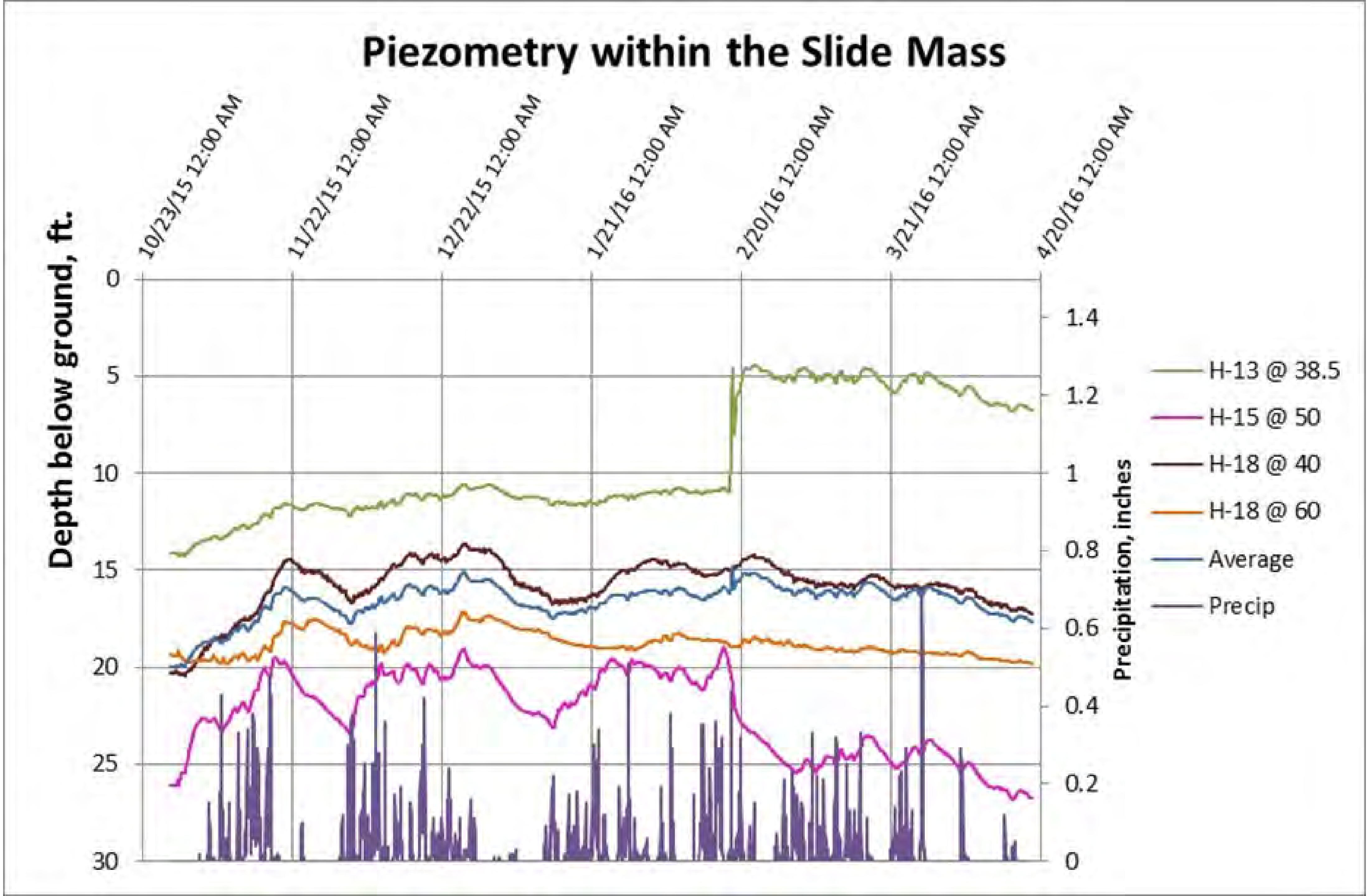

2006 LiDAR
0
750
1500 ft

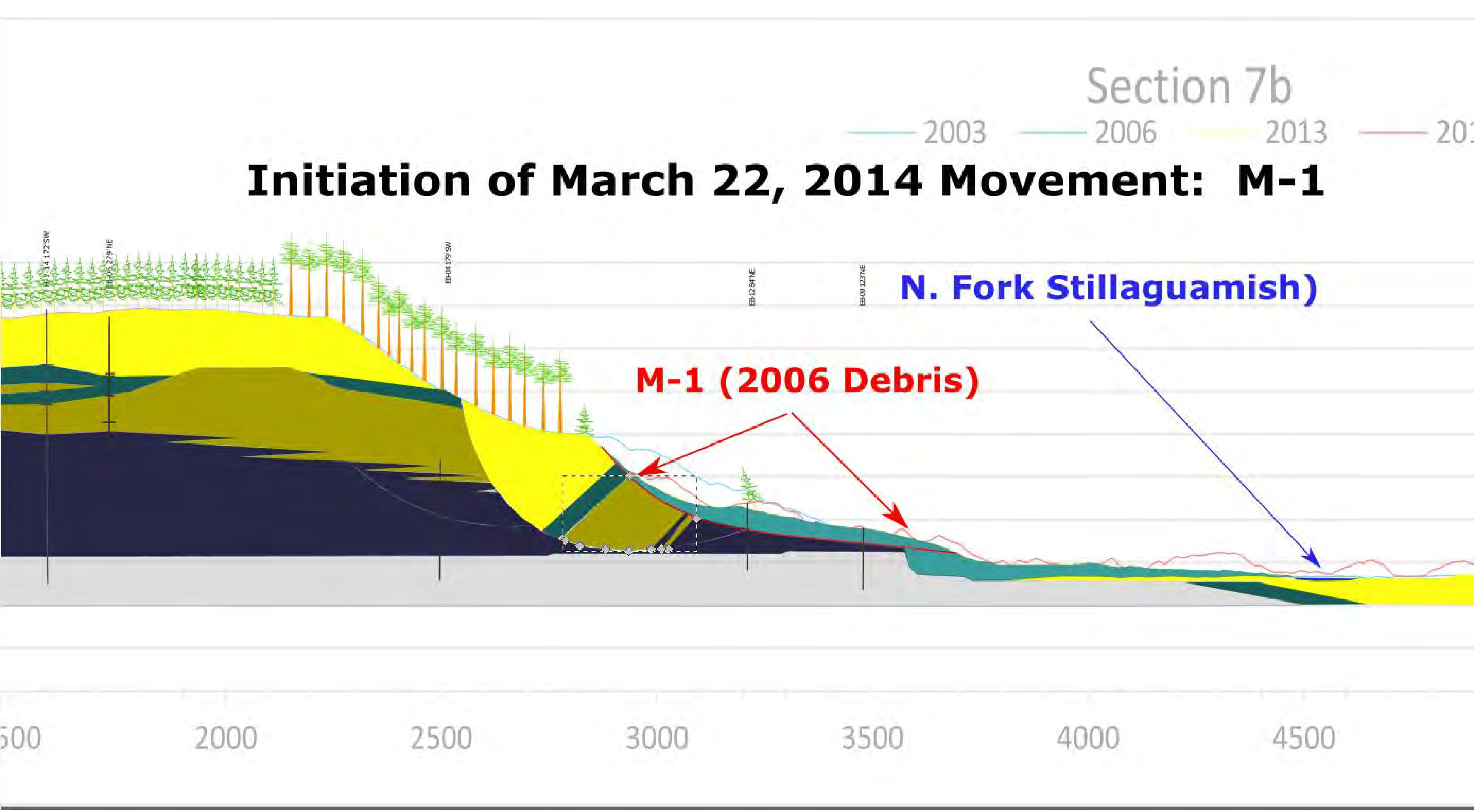

2007


2011

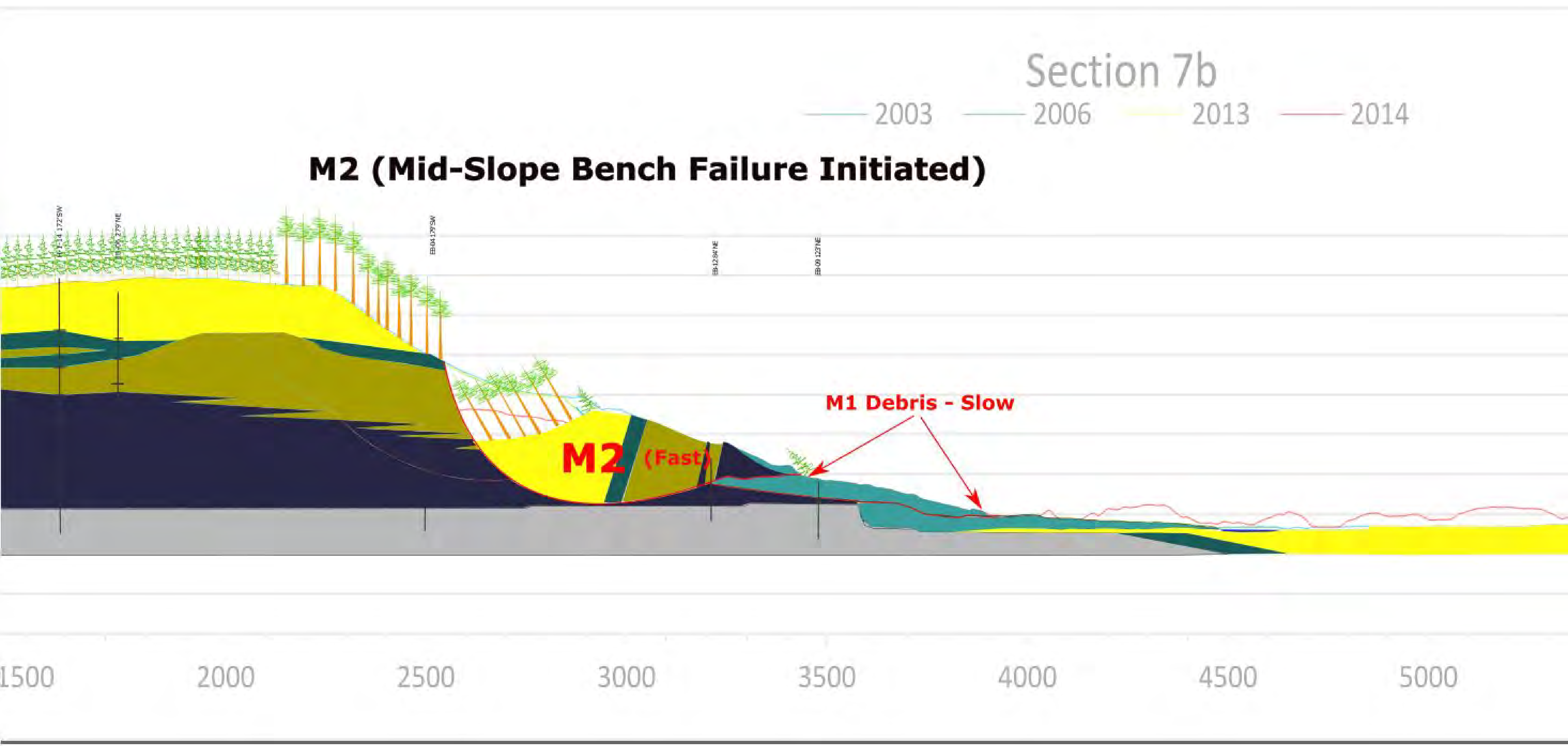

0
750
1500 ft
2013 LiDAR


Section 7b
2003
2006
2013
201
Initiation of March 22, 2014 Movement: M-1
N. Fork Stillaguamish)
M-1 (2006 Debris)
500
2000
2500
3000
3500
4000
4500

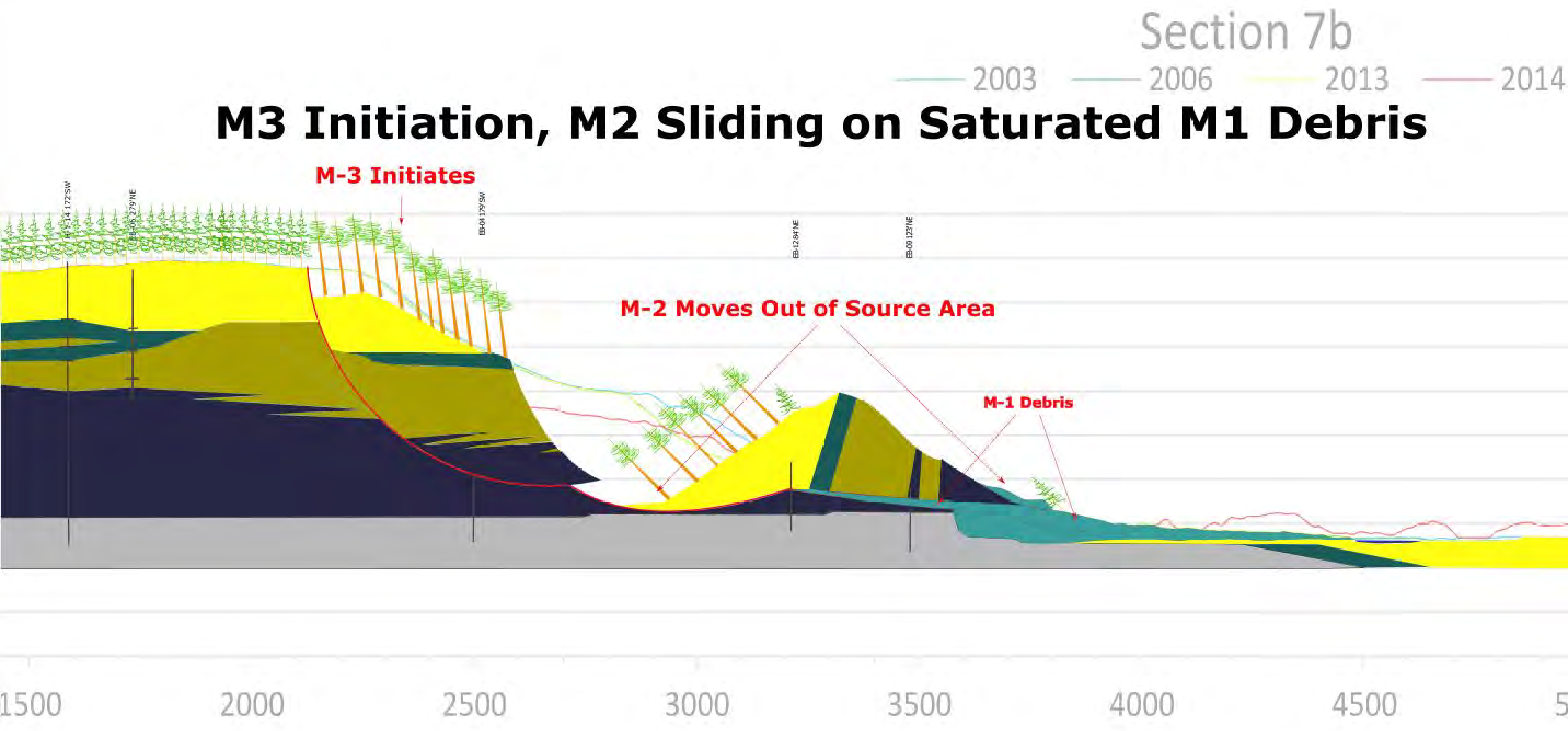

Piezometry within the Slide Mass
Depth below ground, ft.
Precipitation, inches
10/23/15 12:00 AM
11/22/15 12:00 AM
12/22/15 12:00 AM
1/21/16 12:00 AM
2/20/16 12:00 AM
3/21/16 12:00 AM
4/20/16 12:00 AM
0
5
10
15
20
25
30
1.4
1.2
1
0.8
0.6
0.4
0.2
0
H-13 @ 38.5
H-15 @ 50
H-18 @ 40
H-18 @ 60
Average
Precip



Section 7b
2003
2006
2013
201
Initiation of March 22, 2014 Movement: M-1
N. Fork Stillaguamish)
M-1 (2006 Debris)
500
2000
2500
3000
3500
4000
4500



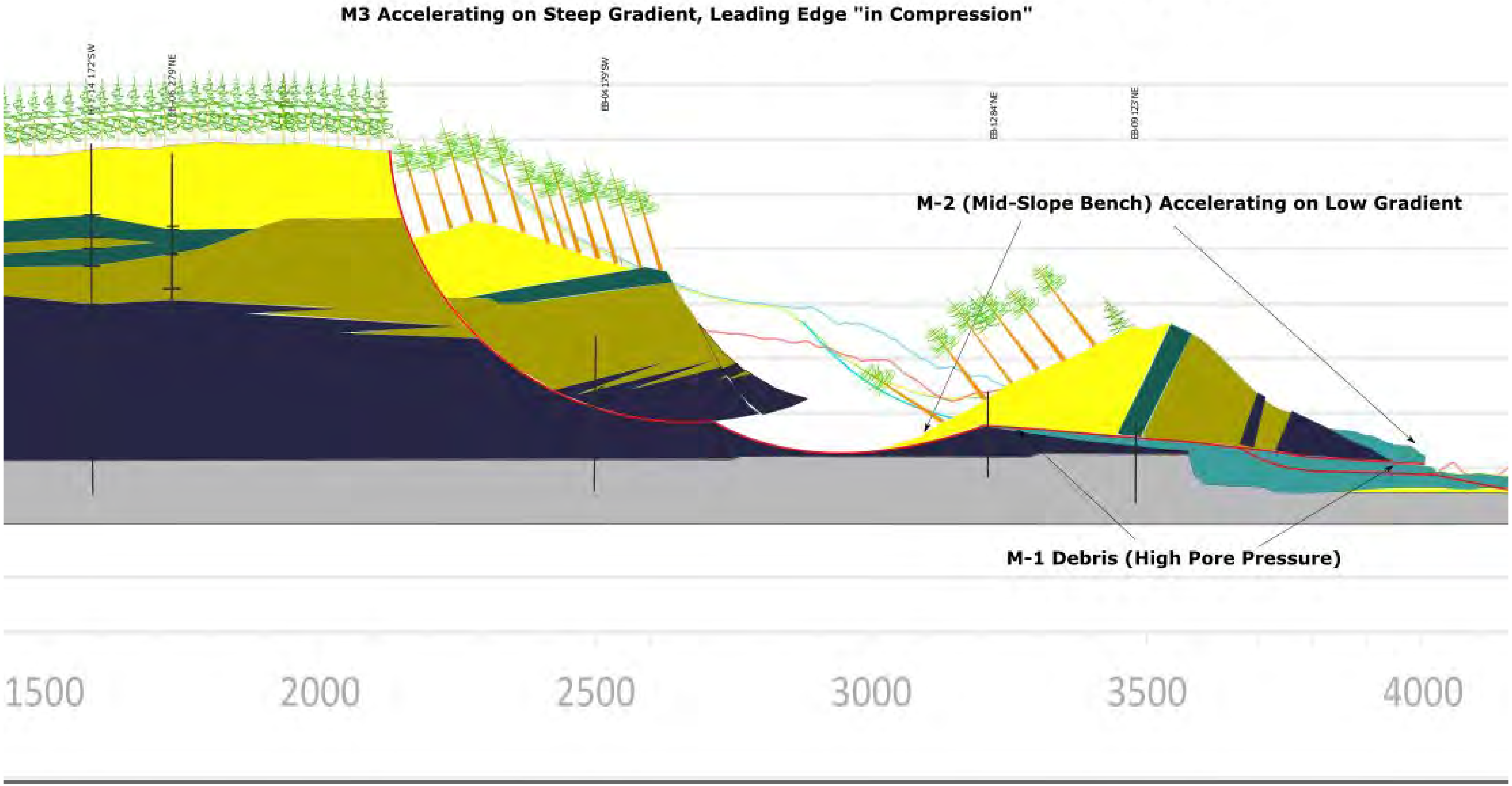
Section 7b
2003
2006
2013
2014
M2 (Mid-Slope Bench Failure Initiated)
M1 Debris - Slow
M2
(Fast)
1500
2000
2500
3000
3500
4000
4500
5000

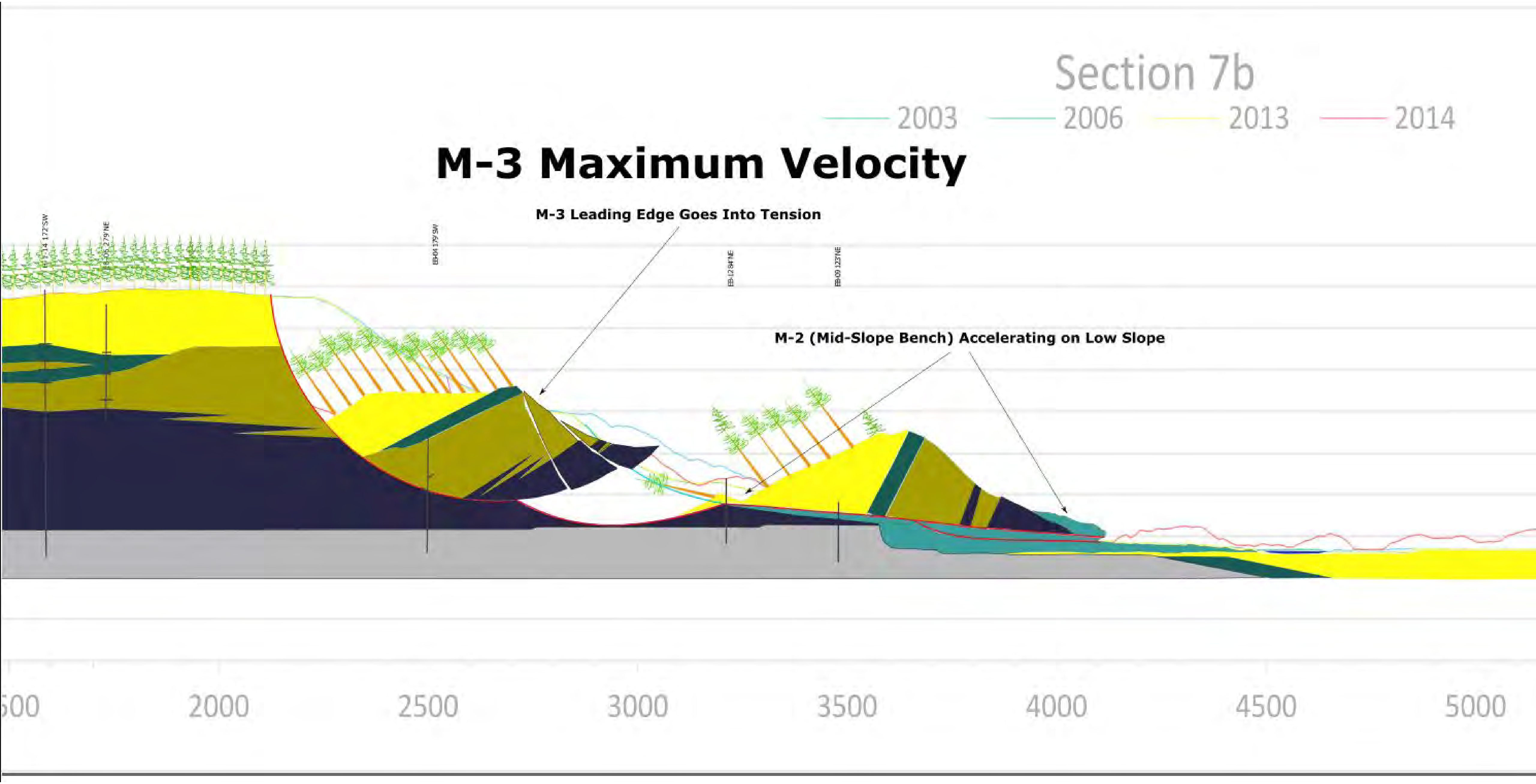

Section 7b
2003
2006
2013
2014
M3 Initiation, M2 Sliding on Saturated M1 Debris
M-3 Initiates
M-2 Moves Out of Source Area
M-1 Debris
1500
2000
2500
3000
3500
4000
4500
5

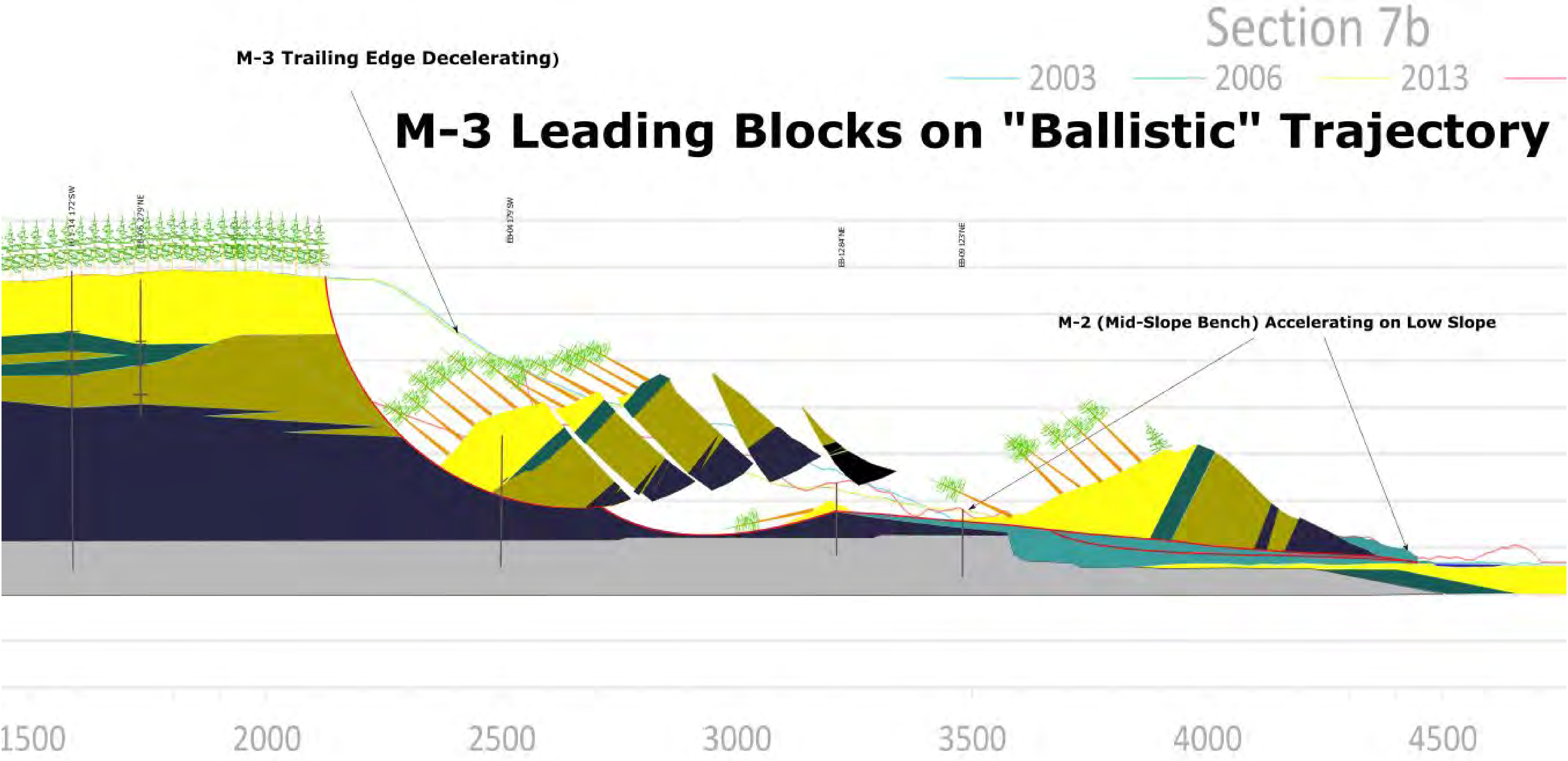
Sec

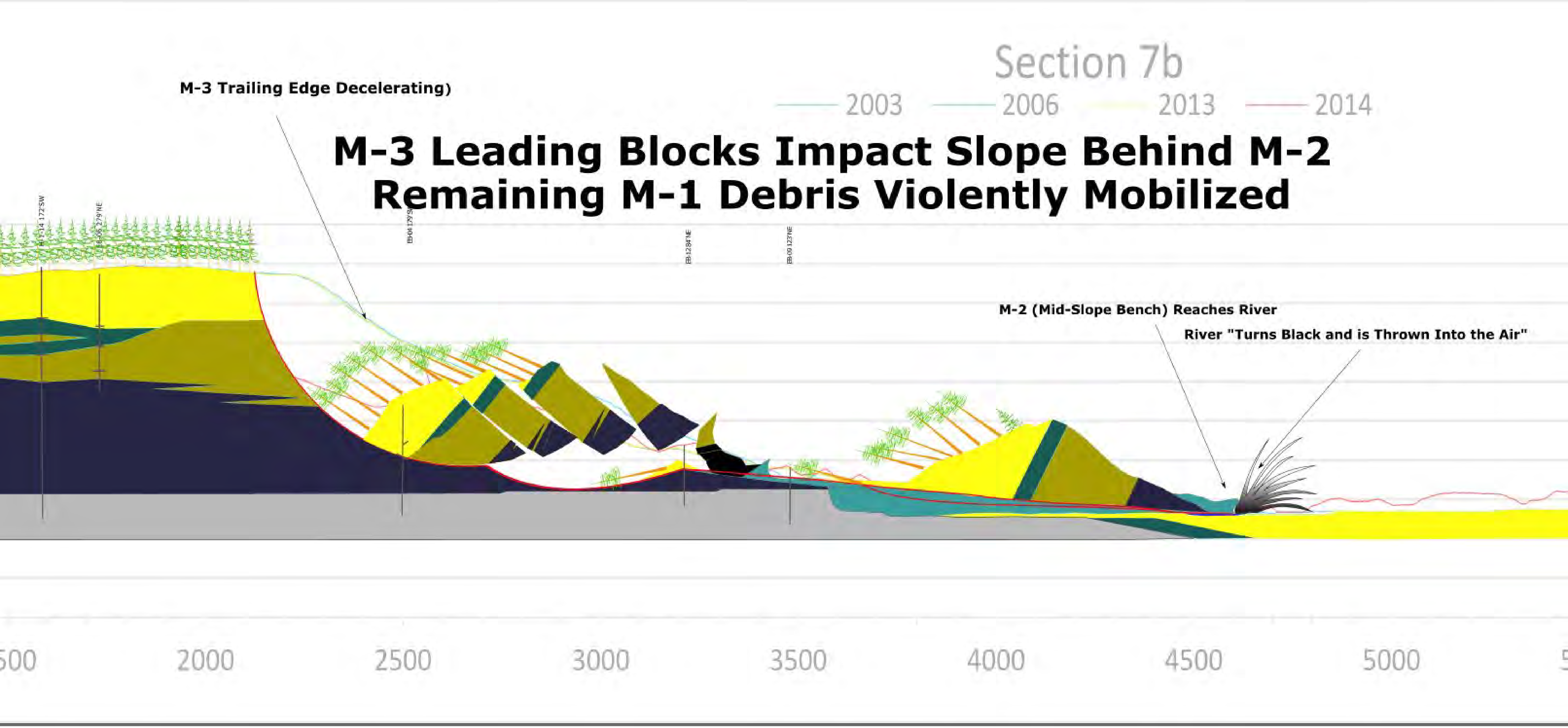
2003 2006

M-2 & M-3 Acceleration




Section 7b
2003
2006
2013
2014
M-3 Maximum Velocity
M-3 Leading Edge Goes Into Tension
M-2 (Mid-Slope Bench) Accelerating on Low Slope
500
2000
2500
3000
3500
4000
4500
5000

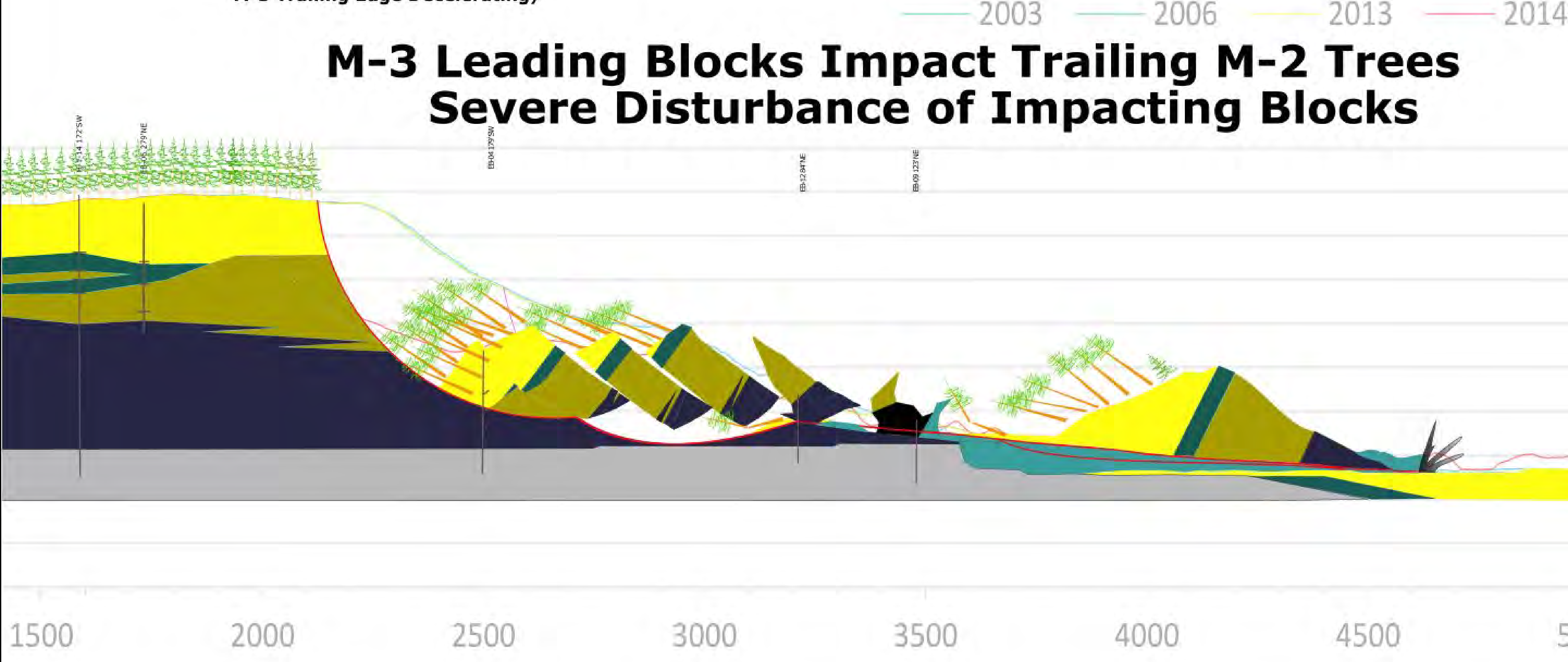

Section 7b
2003
2006
2013
M-3 Trailing Edge Decelerating)
M-3 Leading Blocks on "Ballistic" Trajectory
M-2 (Mid-Slope Bench) Accelerating on Low Slope
1500
2000
2500
3000
3500
4000
4500


Section 7b
2003
2006
2013
2014
M-3 Trailing Edge Decelerating)
M-3 Leading Blocks Impact Slope Behind M-2
Remaining M-1 Debris Violently Mobilized
M-2 (Mid-Slope Bench) Reaches River
River "Turns Black and is Thrown Into the Air"
500
2000
2500
3000
3500
4000
4500
5000

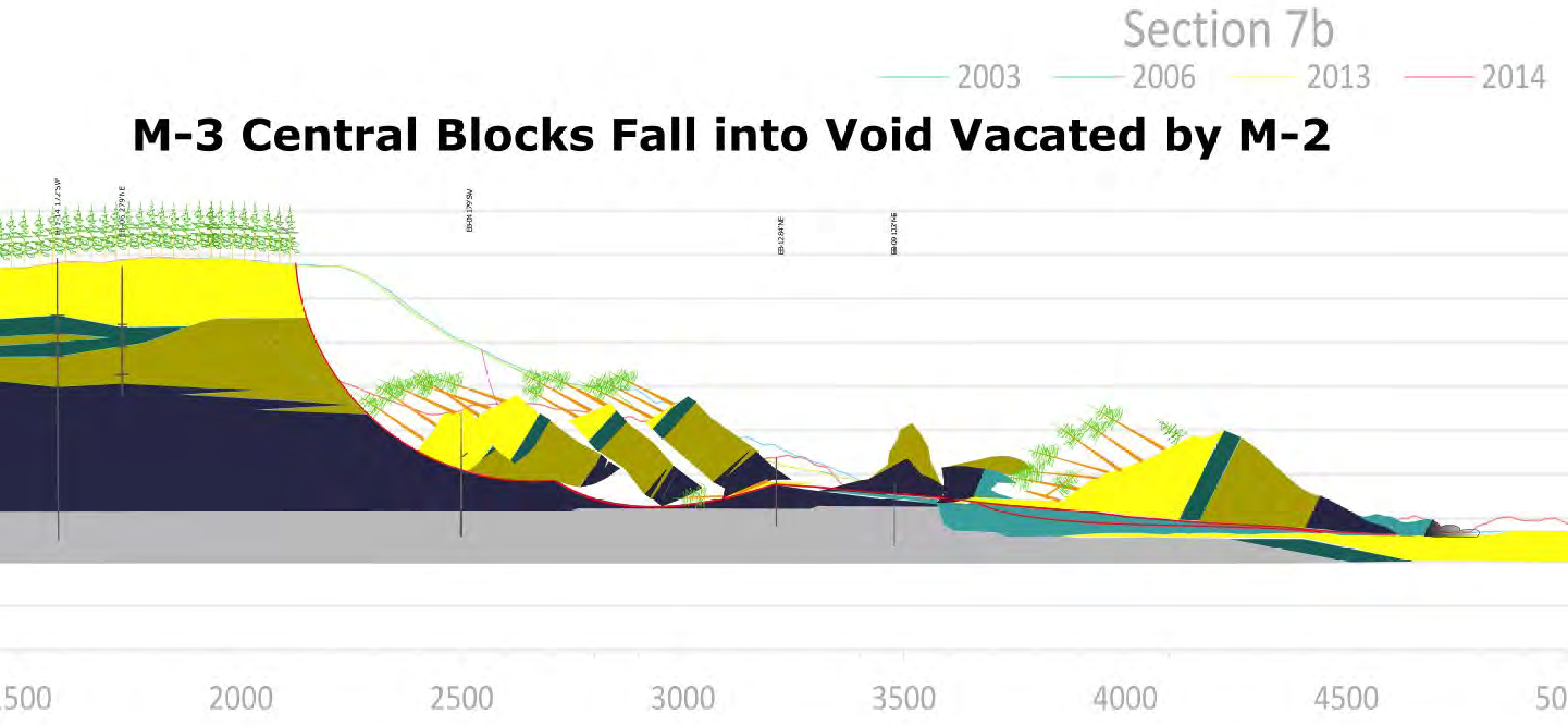
M-3 Trailing Edge Decelerating)

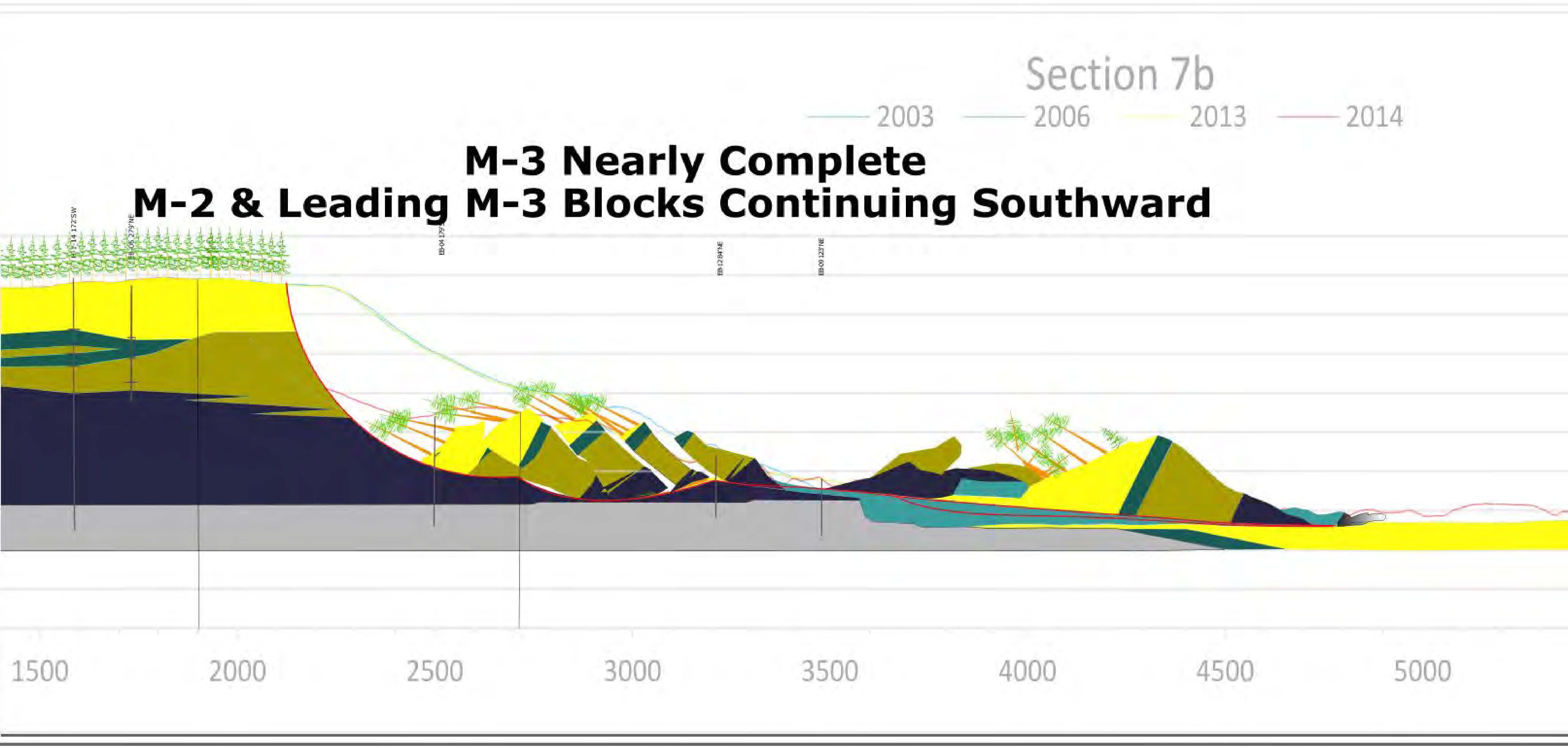
Section 7b

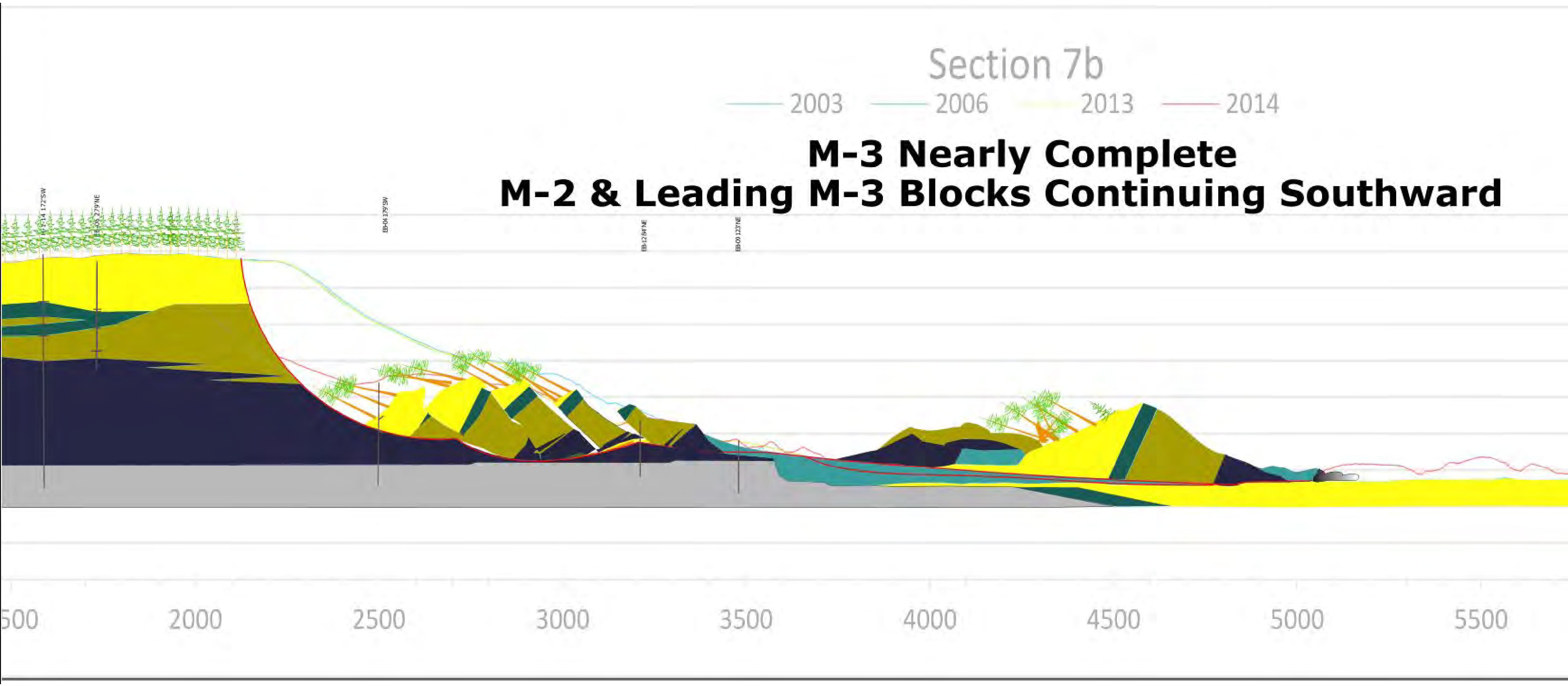
M-3 Leading Blocks Impact Trailing M-2 Trees
Severe Disturbance of Impacting Blocks



M-3 Central Blocks Fall into Void Vacated by M-2

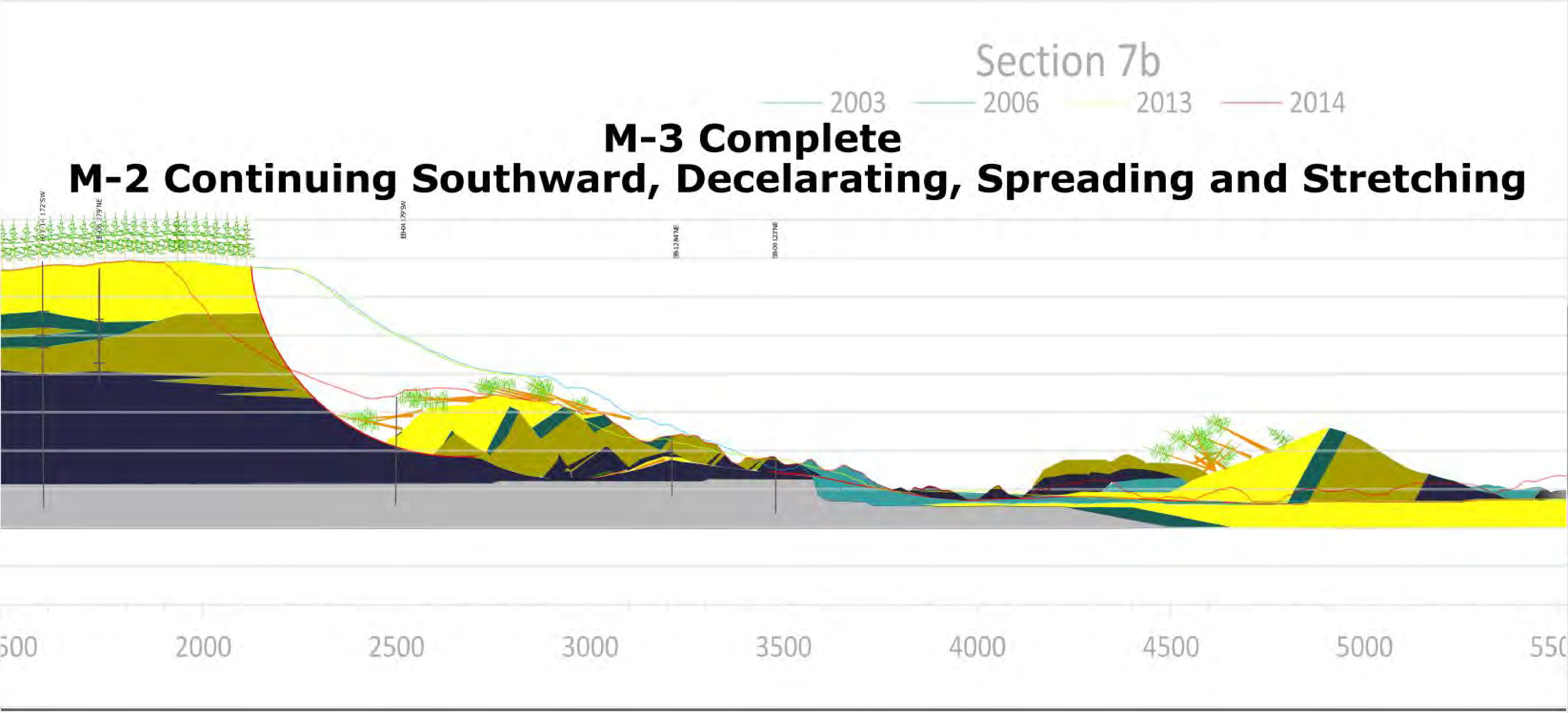


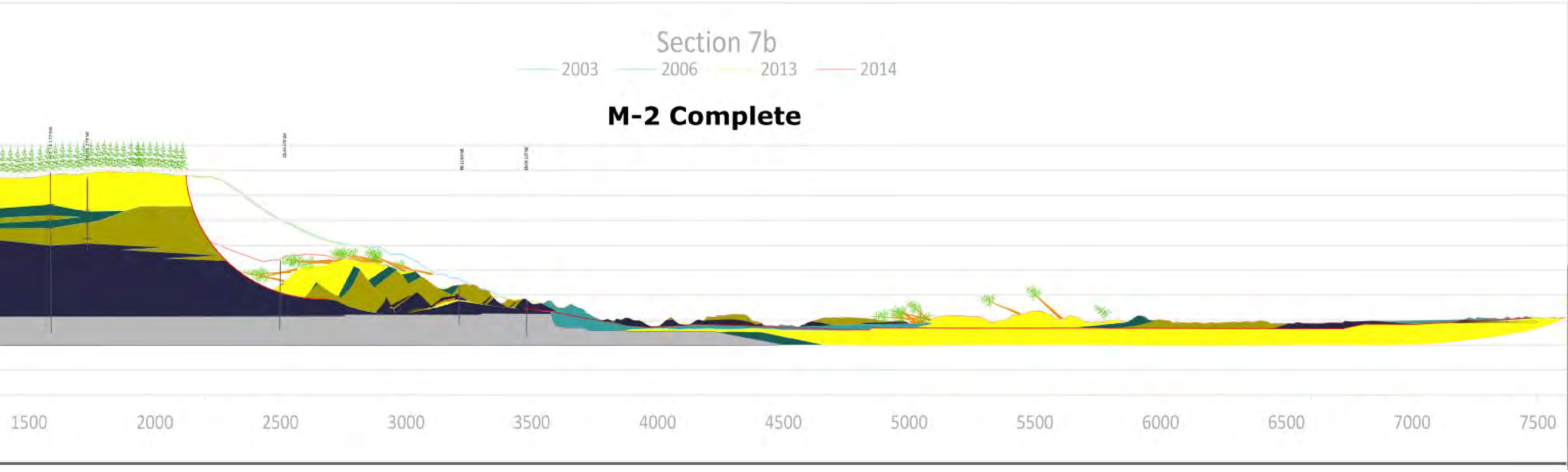

Section 7b
2003
2006
2013
2014
M-3 Nearly Complete
M-2 & Leading M-3 Blocks Continuing Southward
1500
2000
2500
3000
3500
4000
4500
5000

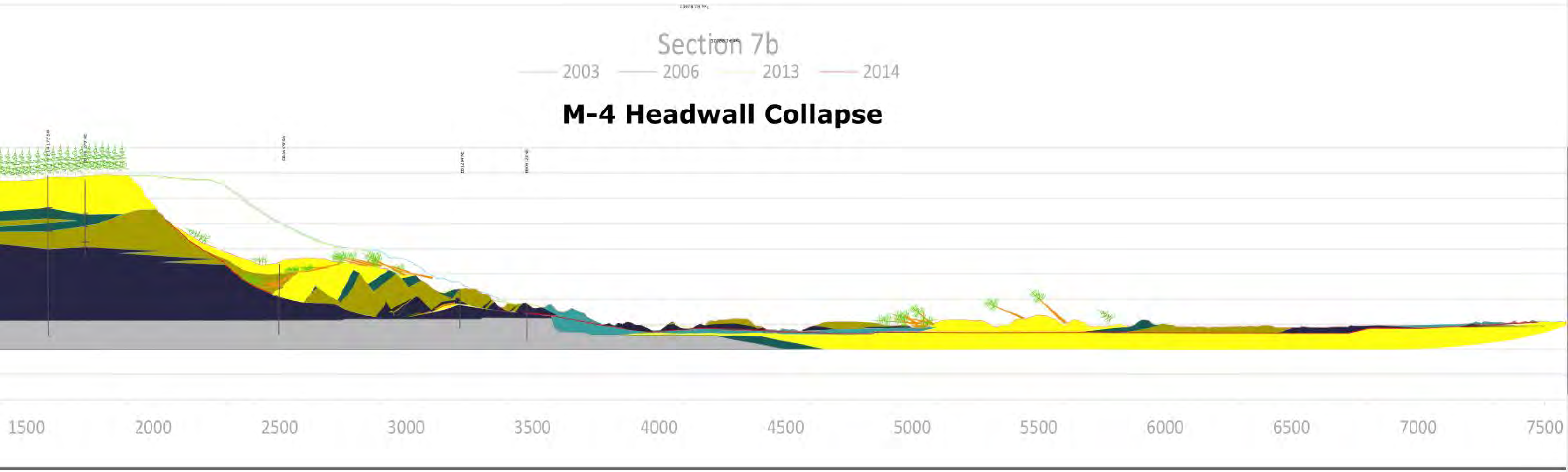


Section 7b
2003
2006
2013
2014
M-3 Nearly Complete
M-2 & Leading M-3 Blocks Continuing Southward
500
2000
2500
3000
3500
4000
4500
5000
5500

M-3 Complete
M-2 Continuing Southward, Decelarating, Spreading and Stretching




Section 7b
2003
2006
2013
2014
M-2 Complete
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500


Section 7b
2003
2006
2013
2014
M-4 Headwall Collapse
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500

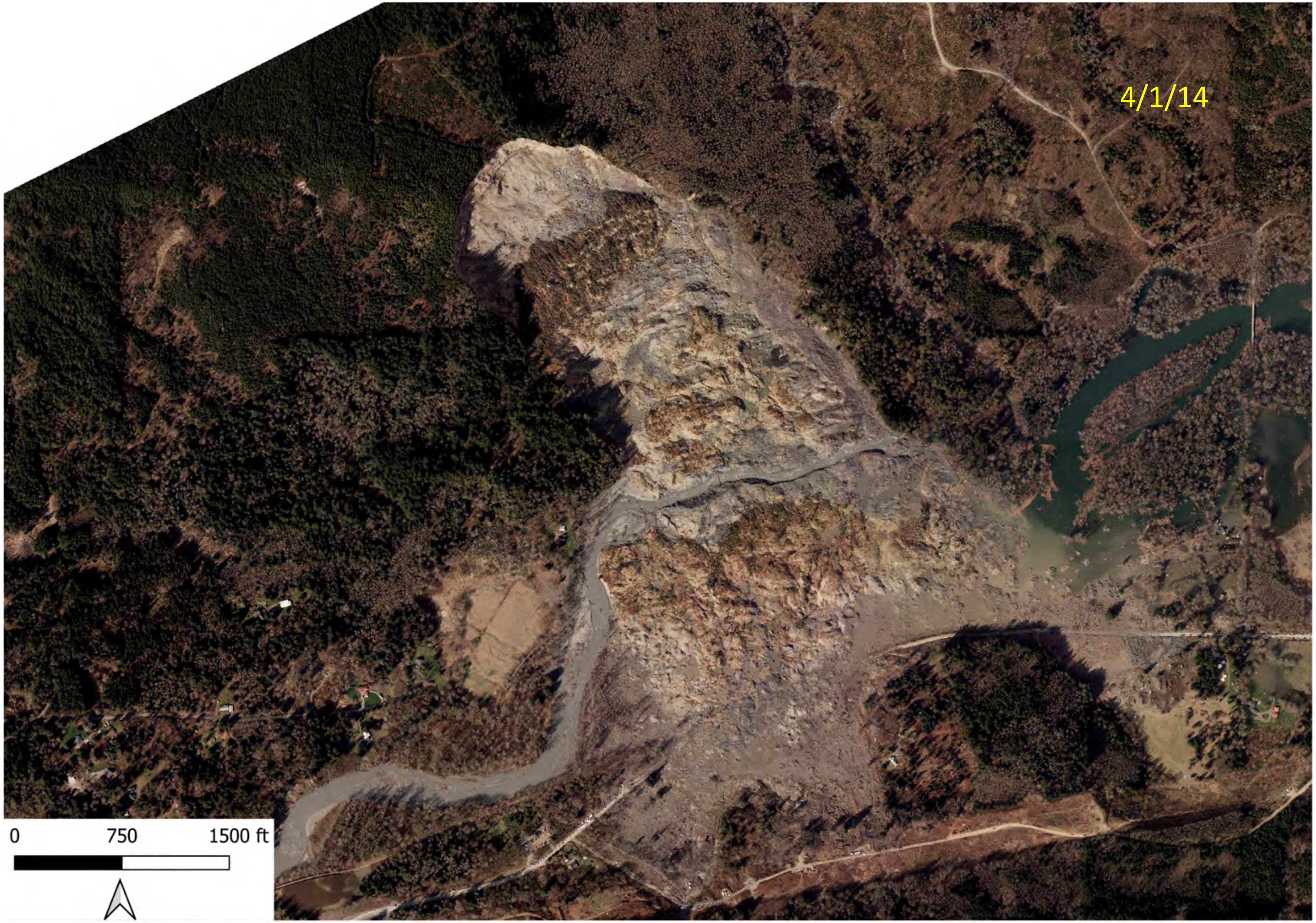
4/29/2014
Photo Courtesy Tom Badger
(Formerly WSDOT)


0
500
1000
1500 ft


N


N


N



4/1/14
0
750
1500 ft


2018
SR 530
SR 530
0
750
1500 ft
River Has Moved NW a Maximum of 175' in 4 Years

IN SUMMARY:

- The Original Failure of the Mid-Slope Bench Dates to the End of the Last Ice Age
- Little Slope Movement Activity at the Site From +/-13,000 YBP Until the Early 1900s
- Significant Slope Movement Since the 1930s In Response to Erosion by NF
- There were Two Larger Events Prior to 2014, in 1967 and 2006.
- Slides of the last 100 Years Unloaded the Toe of the Mid-Slope Bench Failure P-2.
- There is no Evidence that Human Activity Contributed to the Oso Slide.
- The March 22, 2014 Event Unfolded in 4 Phases:
    - M-1 Minor Sliding of 2006 Slide Debris
    - M-2 Reactivation of Ice-Age P-2
    - M-3 Response of Previously Stable Portion of Kame Terrace (Whitman Bench)
    - M-4 Head Scarp Collapse.

RECOMMENDATIONS:

- Resume Monitoring of the Current Slide Area (all Instrumentation has been Removed) This seems to be an inappropriate stick-your-head-in-the-sand approach
- Conduct Boots-on-the-Ground Assessments of Similar Geomorphic Features in Vicinity (DNR is apparently planning to do this in a limited fashion shortly).
- Form a Consortium of Stake Holders (Including Government Regulators, Tree Farmers, and Environmental Groups) to Devise Strategies to Address/Assess the Dominant Paradigm that "Logging Causes Landslides". This idea, which started in the 1930s or before, is counterproductive for all interests as it implies that everyone would be "safe but for logging." I realize that the rule-making process was structured somewhat similarly to this idea, but it did not involve actual investigations.
- No Worries for Oregonians of the same thing happening! Oregonians can instead worry about garden-variety non-glacial landslides (some bigger than Oso) and debris flows.