Deep Seated Landslide Mapping & Classification Project

Presentation of Study Design to the Cooperative Monitoring, Evaluation, and Research Committee

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April 25, 2023

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Agenda

Intro and Background

Deep Seated Landslides in Washington State
Washington Deep Seated Landslide Strategy Overview

Mapping and Classification Study Design

Mapping and Classification Project Objectives
Data Availability
Activity Classification
Landslide Activity State Designations
Developing Landslide Classes
Assessing Sensitivity of Landslide Classes
Proposed Study Area

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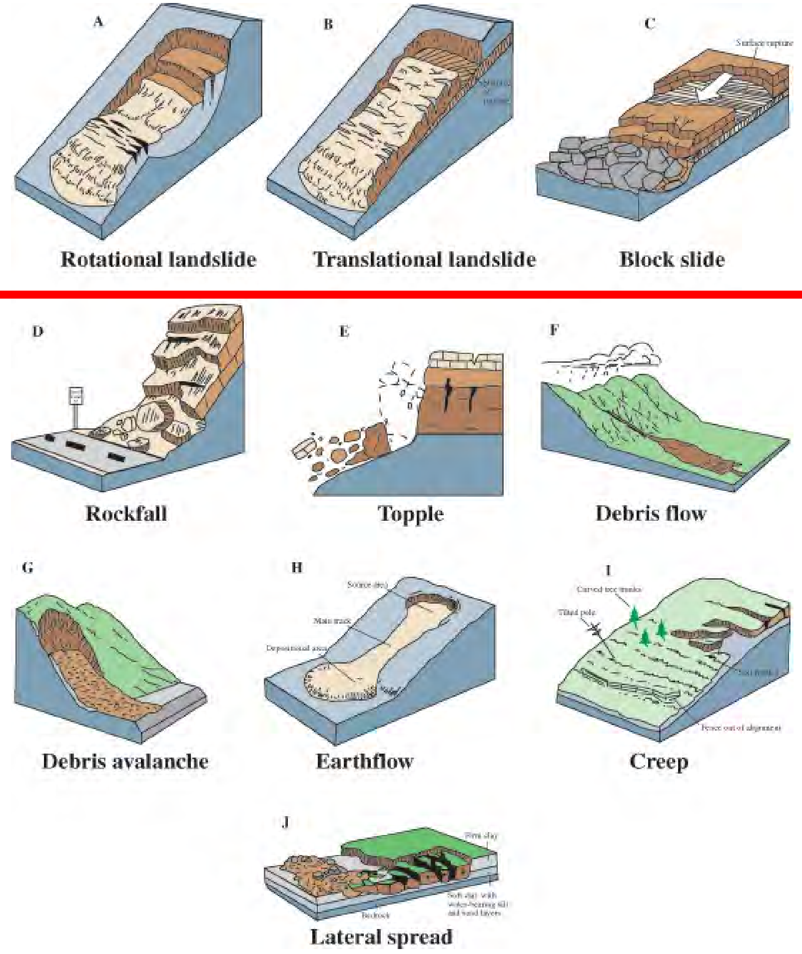
Deep Seated Landslides

Landslide Types and Sensitivity

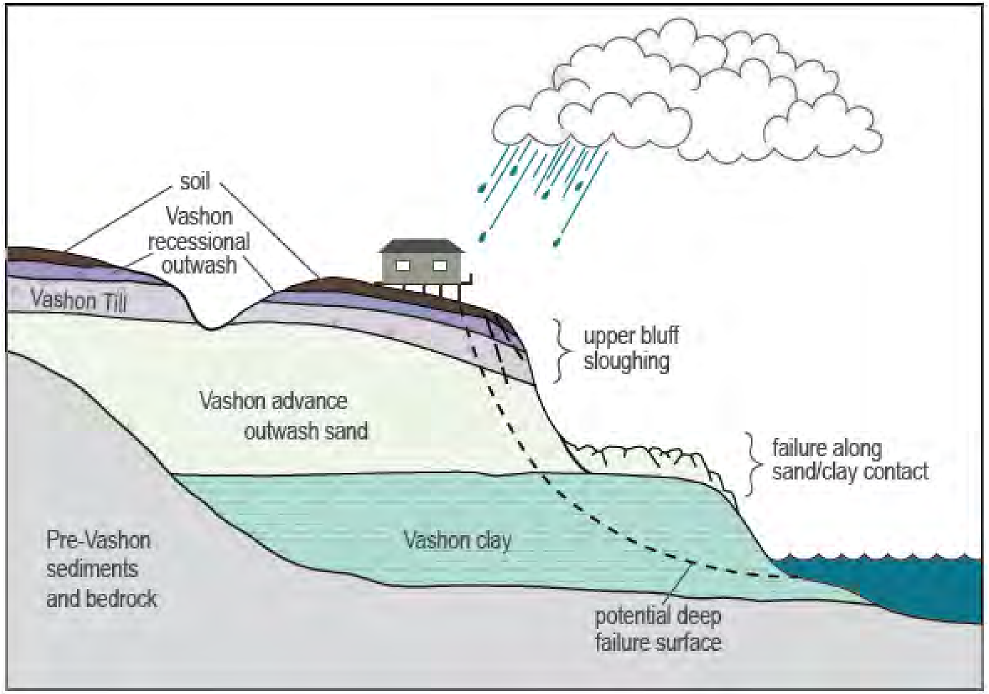
Where do Deep Seated Landslides Fit?



Class	Description	Typical velocity	Proposed annual displacement criteria (m)	Proposed mean annual displacement (m)
7	Extremely rapid	>5 m/sec		
6	Very rapid	>3 m/min		
5	Rapid	>1.8 m/hr		
4+	Moderate	>13 m/month	>16	64
3	Slow	>1.6 m/yr	>1.6	6.4
2b	Very slow	>160 mm/yr	>0.16	0.64
2a	Very slow	>16 mm/yr	>0.016	0.064
1	Extremely slow	<16 mm/yr	>0.0016	0.005
0	Dormant	0 mm/yr	<0.0016	0

Types of Deep Seated Landslides in Washington State

Landslides in Glacial Sediments

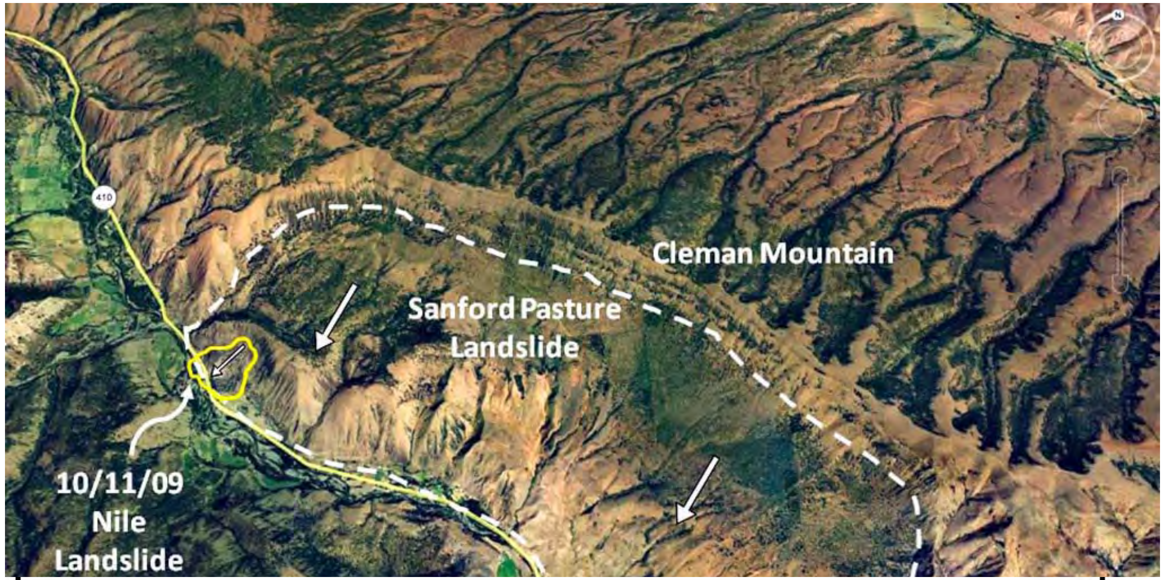


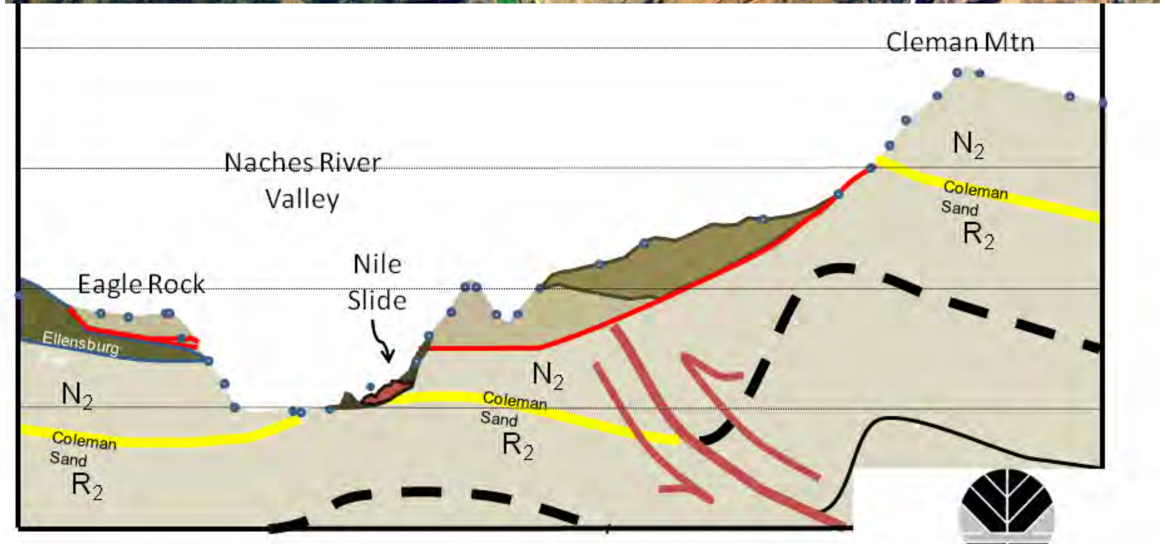
Mickelson, K. A.; Jacobacci, K. E.; Contreras, T. A; Biel, Alyssa; Slaughter, S. L., 2017, Landslide inventory, susceptibility, and exposure analysis of Pierce County, Washington: Washington Geological Survey Report of Investigation 39, 16 p. text, with 2 accompanying ESRI file geodatabases and 1 Microsoft Excel file. [https://fortress.wa.gov/dnr/geologydata/publications/ger_ri39_pierce_county_landslide_inventory.zip]

Types of Deep Seated Landslides in Washington State

Landslides in Bedrock

Photo: WSDOT



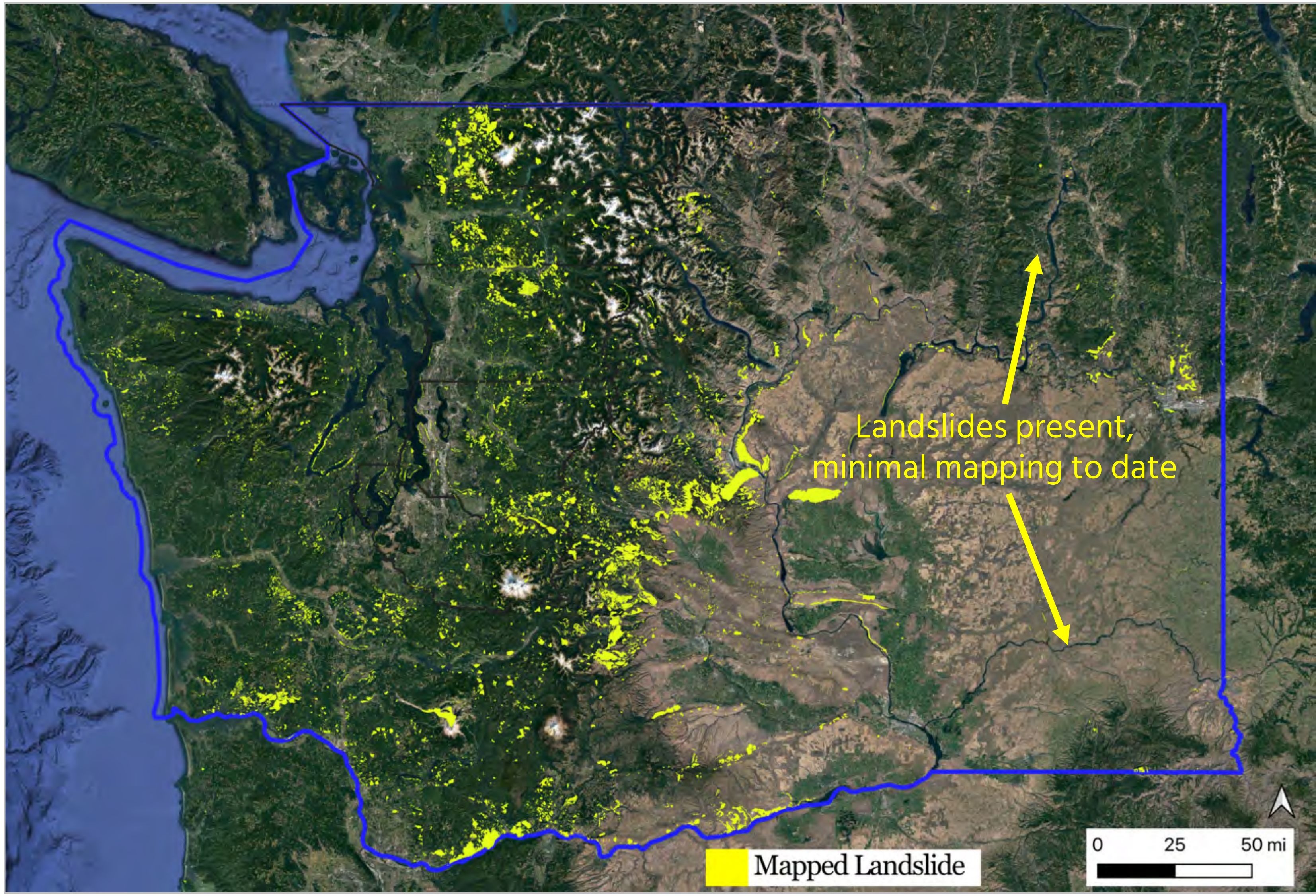


WASHINGTON STATE DEPARTMENT OF
Natural Resources

Distribution of Deep Seated Landslides in Washington State

Location/Density of Mapped Landslides

- Occur east to west, north to south
- Most mapping performed adjacent to the Cascade crest and east
- River valleys, steep



~130,000 mapped landslides across Washington State

Sources: Washington Geological Survey, Forest Practices Board, Miller 2016, Miller 2017, Xu et al., 2021

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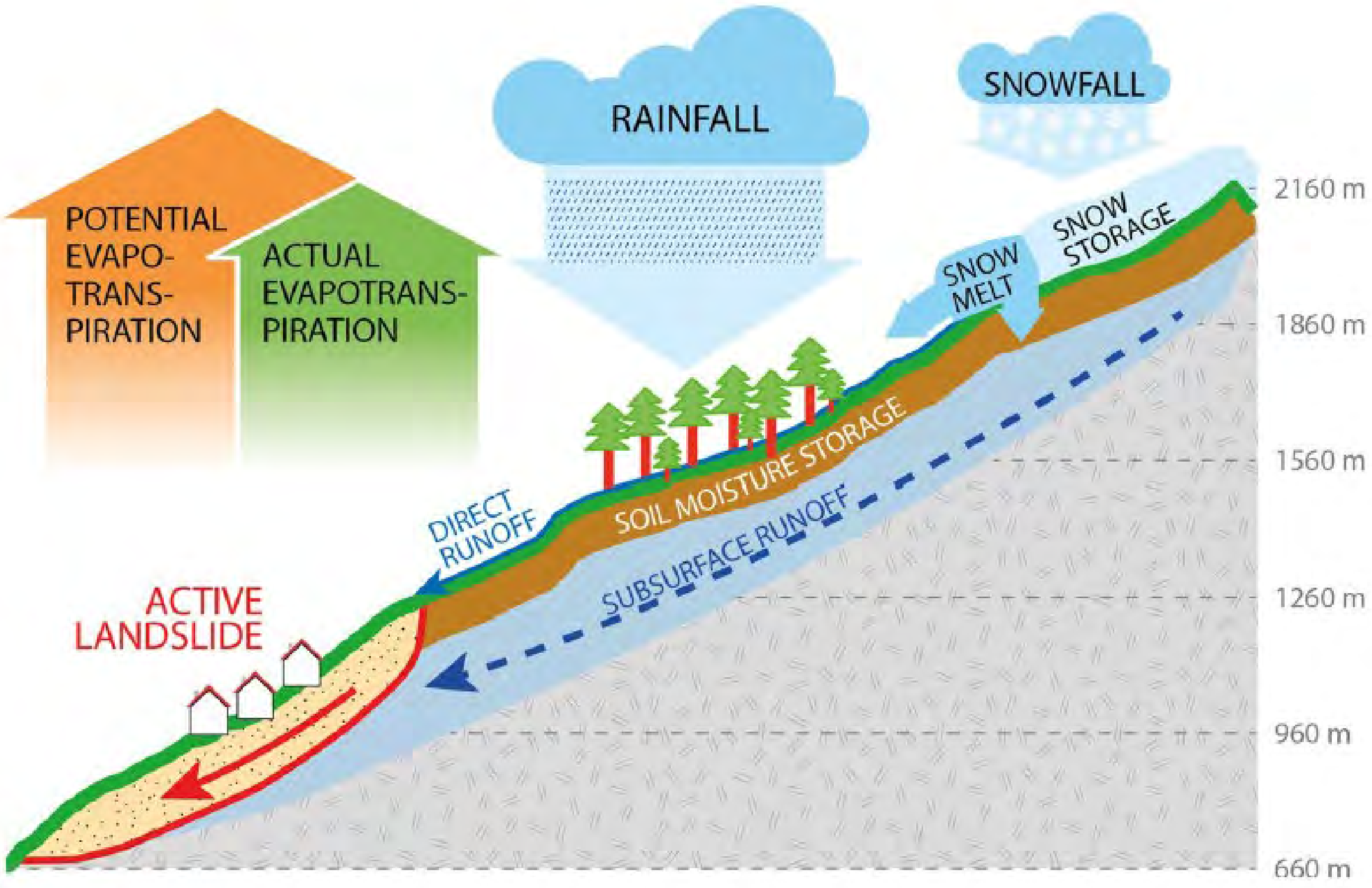
What Drives Activity Changes in Deep Seated Landslides

Natural and Human Interactions

For deep seated landslides, the amount of water that infiltrates and builds up pressures in the subsurface will drive activity change

Human interactions that both change how and where water infiltrates can also lead to activity changes (water diversion, reduction of evapotranspiration)



Zieher, T., Gallotti, G., Rianna, G. *et al.* Exploring the effects of climate change on the water balance of a continuously moving deep-seated landslide. *Nat Hazards* **115**, 357–387 (2023). https://doi.org/10.1007/s11069-022-05558-7

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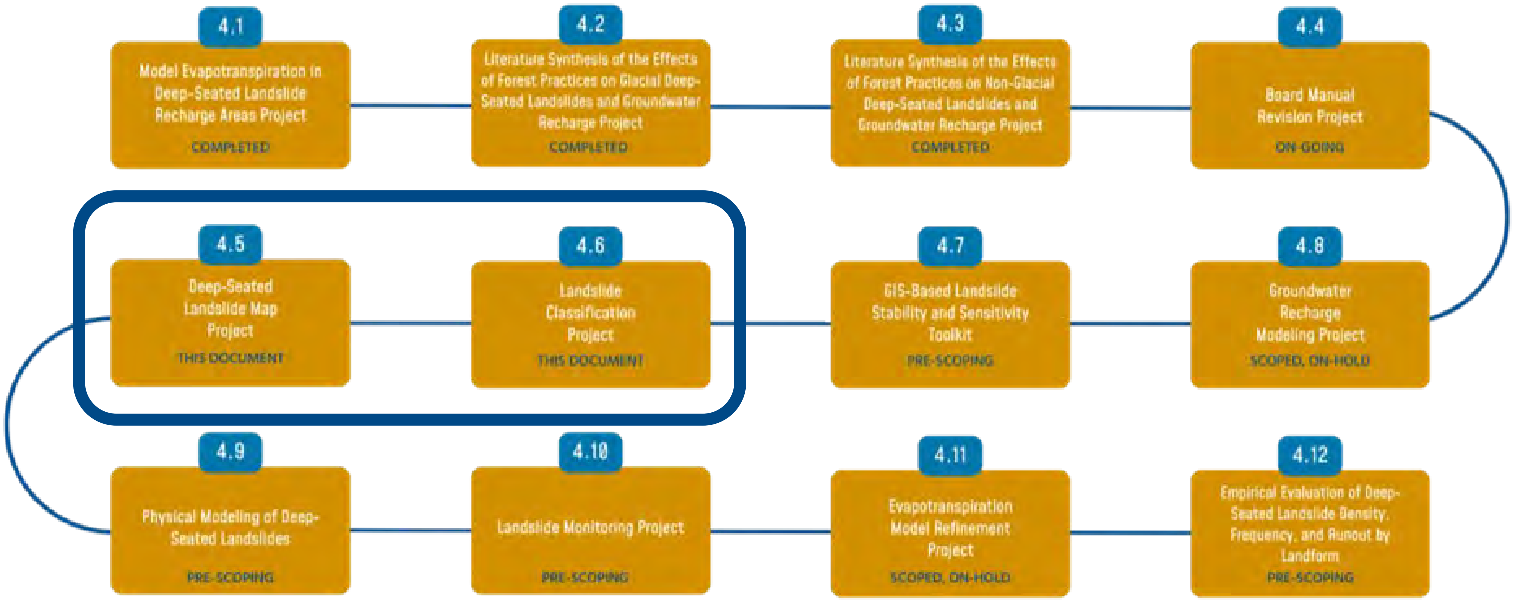
Deep Seated Landslide Strategy

Critical Questions

1. Can relative levels of response to forest practices be predicted by key characteristics of glacial deep-seated landslides and/or their groundwater recharge areas?
2. Does harvesting of the recharge area of a glacial deep-seated landslide promote its instability?
3. Are unstable landforms being correctly and uniformly identified and evaluated for potential hazard?



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Mapping and Classification Study

Mapping and Classification Project

Purpose and Critical Questions

The Landslide Mapping & Classification Project is intended to provide a classification of deep-seated landslides inferred to represent a range of potential landslide susceptibility to natural and forest practice triggers. This effort will provide the framework needed to pursue additional projects as described in the Deep-Seated Landslide Research Strategy (CMER 2018).

1. Identify **distinguishing characteristics within and between DSLs** with similar geomorphic, topographic, stratigraphic, hydrologic, and climate settings.
2. Investigate why **landslides with similar characteristics may exhibit differences in activity level.** Can activity levels of individual DSLs within and between clusters be linked to sensitivity to hydrologic or other change?
3. Develop **causal mechanism hypotheses** for individual landslides evaluated in the field. These mechanisms might be evident through hydrogeologic characteristics visible in active landslides.
4. Determine the **best remote sensing tools, field assessment and other methods** to classify DSLs in a manner that will improve our understanding of the relative potential for DSL reactivation or accelerated movement. What data are necessary to estimate the relative sensitivity of DSLs within a class?
5. **Define classes of DSLs** within and across clusters using a suite of physical attributes based on critical independent variables. These classes will also be used to support future phases of the research strategy (i.e., which DSLs are most representative or illustrative for future research and modeling efforts based on the results of the classification project). What are the critical independent (predictor) variables necessary to define DSL classes?
6. Evaluate if certain classes of landslides have a high or low **potential for instability from forest practices** and rank classes based on multiple sources of empirical evidence.

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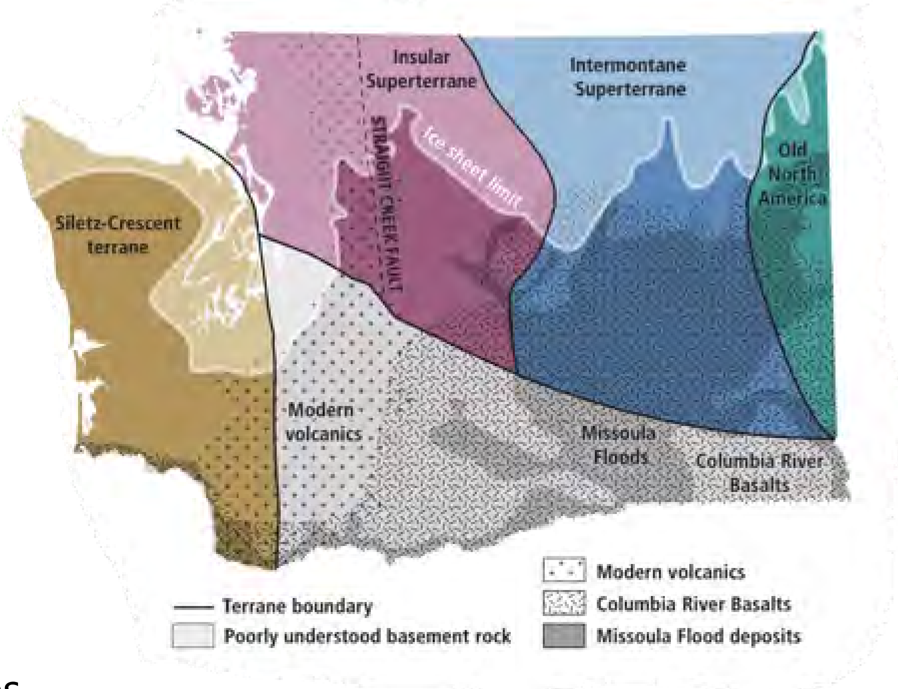
Objectives and Approach

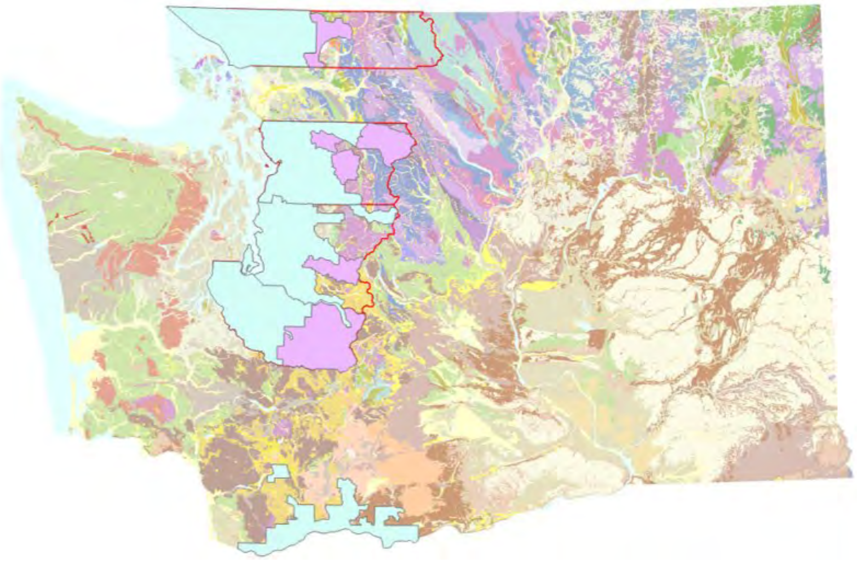
Objective 1

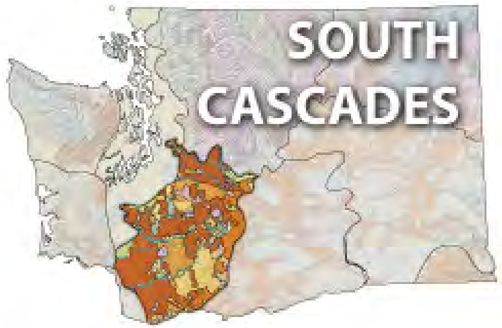
Defining Classes

To identify distinguishing characteristics within and between similar DSLs

- Physiography
- Geology
- Structure
- Spatial distribution of mapped landslides
- Relative age
- Surface water drainage
- Hydrology
- Climate/vegetative zoning







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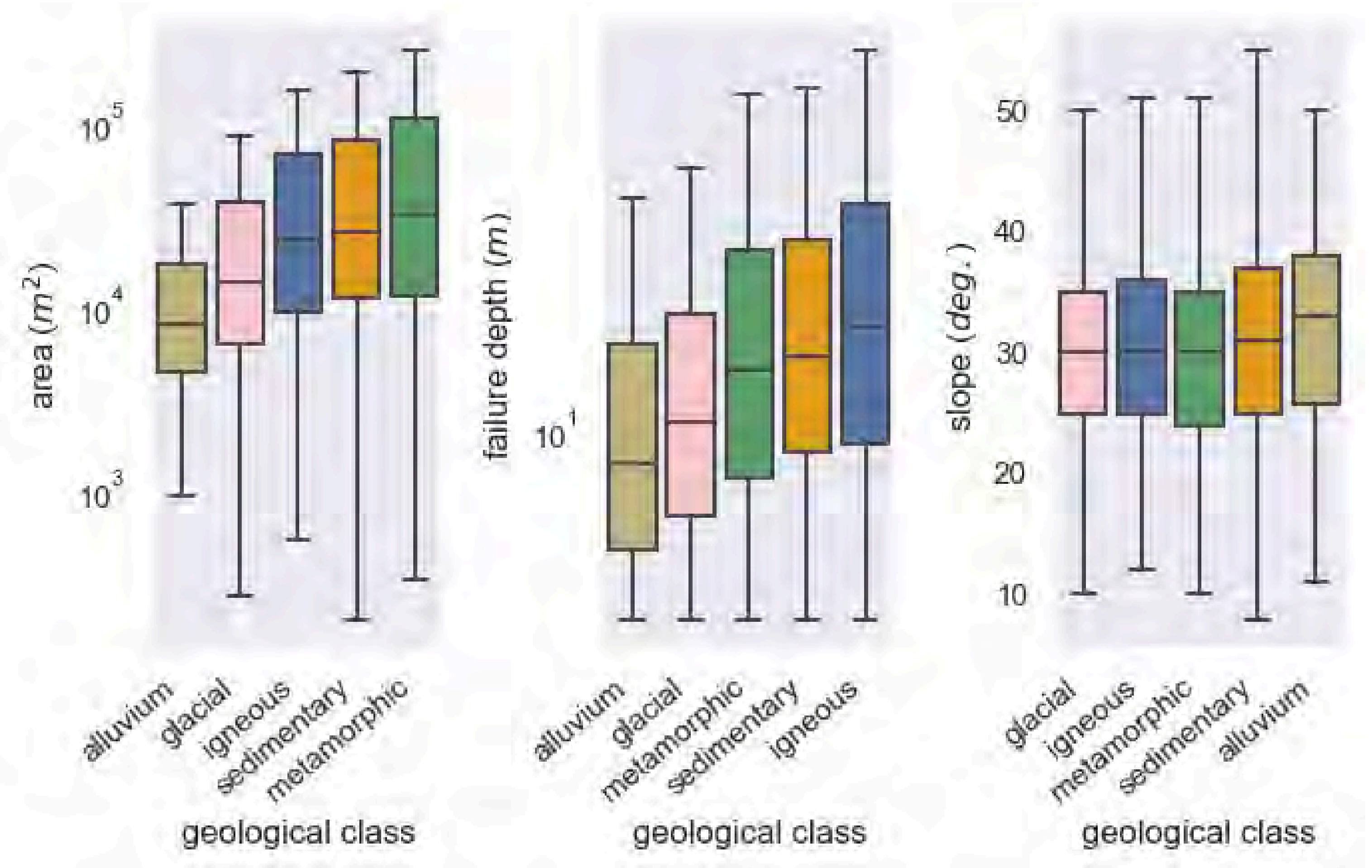

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Objective 2

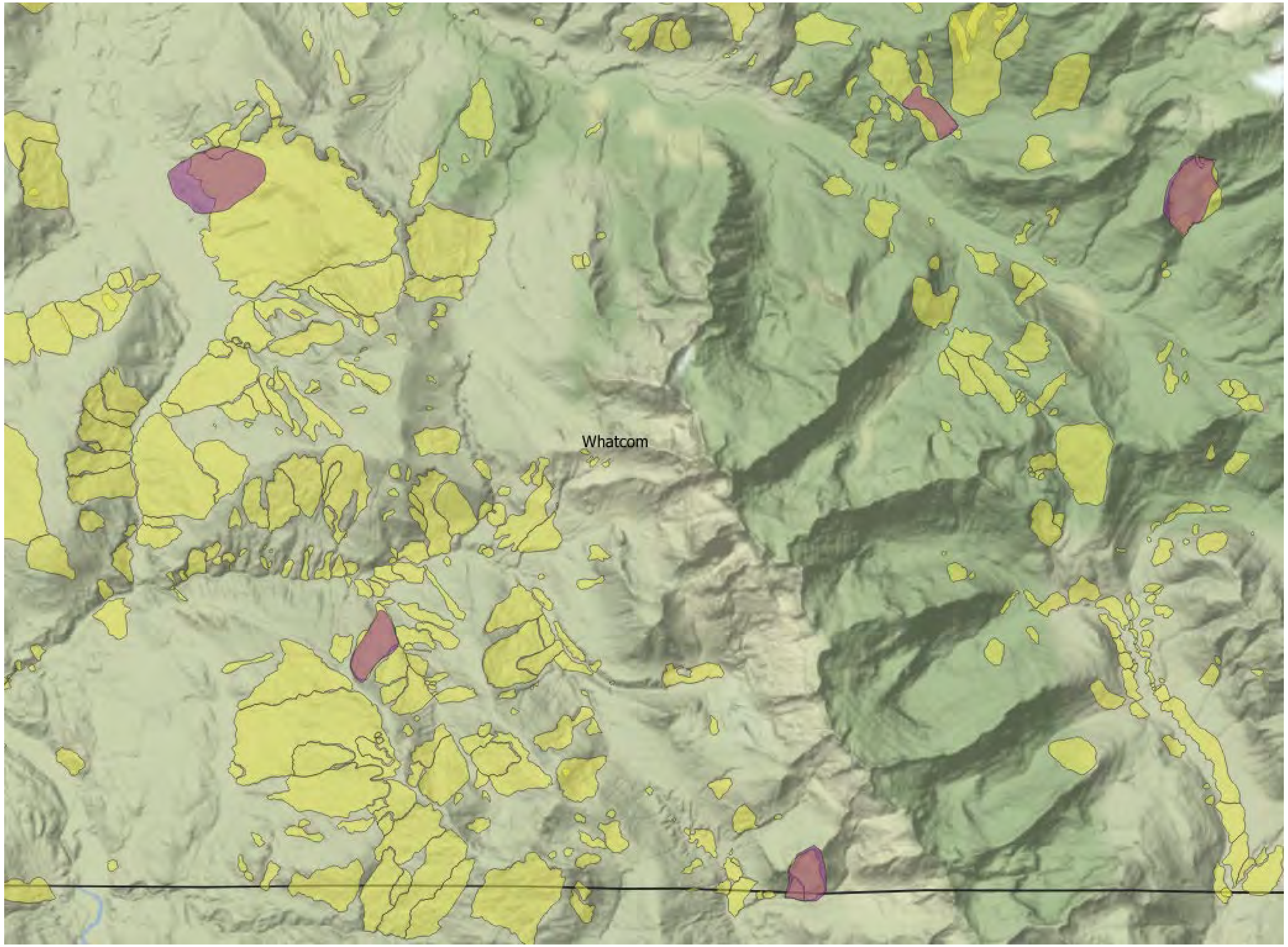
Mapping Activity Variability

Investigate why landslides with similar characteristics may exhibit differences in activity level.

Can activity levels of individual DSLs be linked to sensitivity to hydrologic or other change?

To answer this, we must first answer:

What landslides are moving relative to total population?

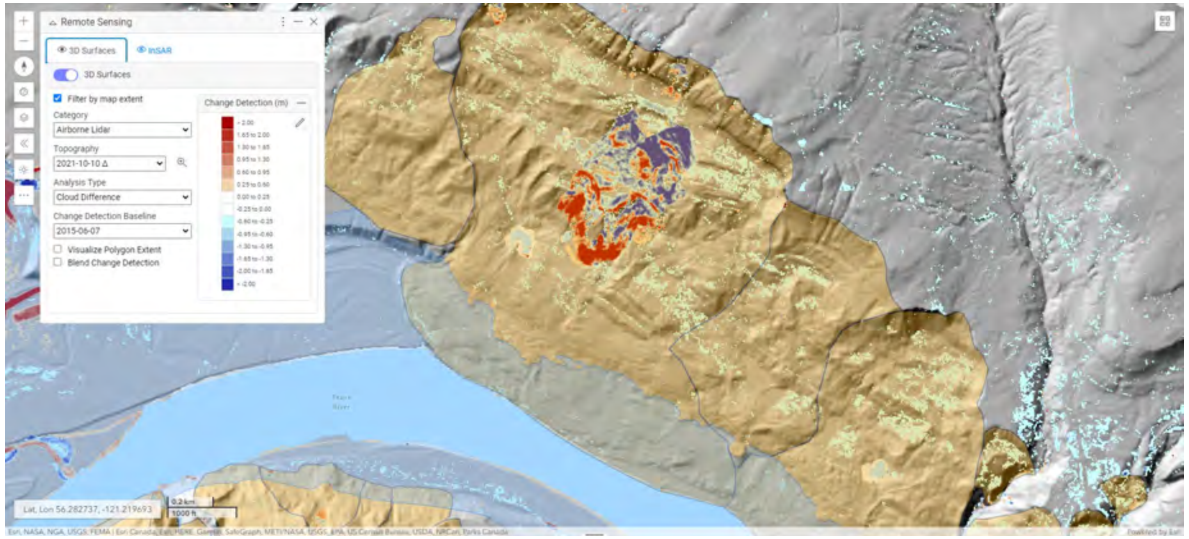


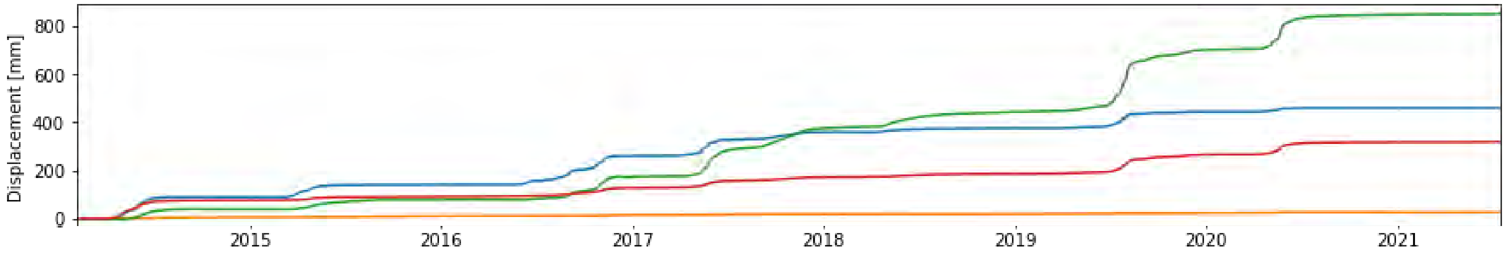
How do we map activity variability?

Activity Data Sources

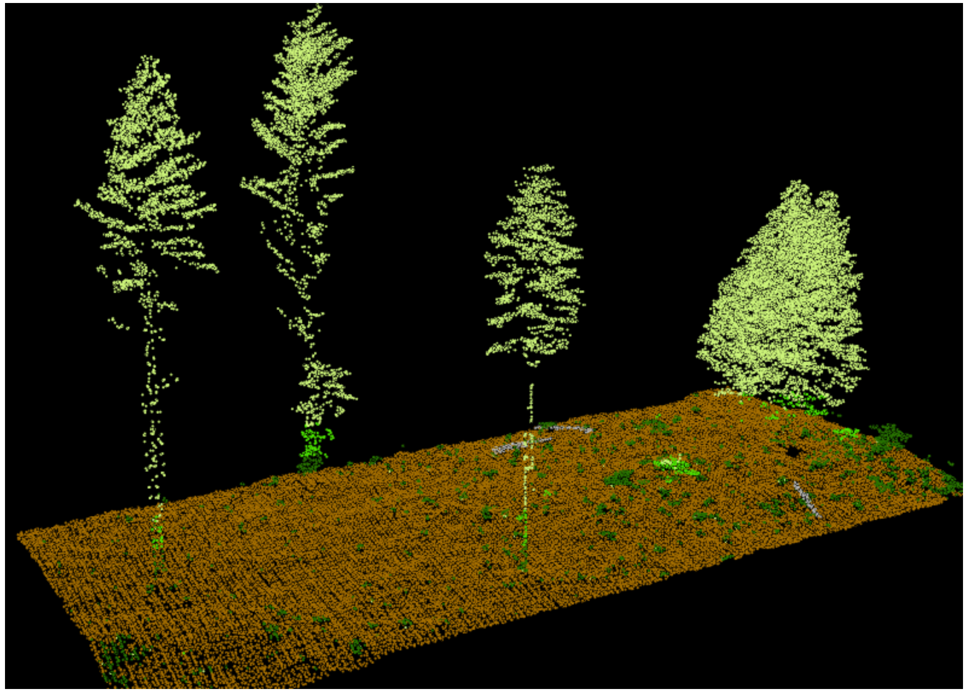
What types of data are available to provide the best opportunity to provide both spatial and temporal deformation patterns:

- **Lidar**
- **InSAR**
- Instrumented sites
  - Washington DOT
  - Forest Service
  - County and City Sites
- Regional observations
- Site specific observations

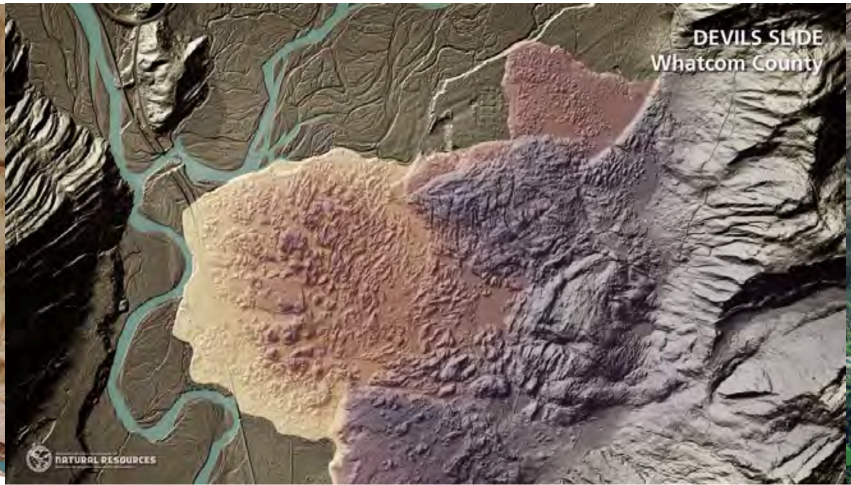




Lidar 101

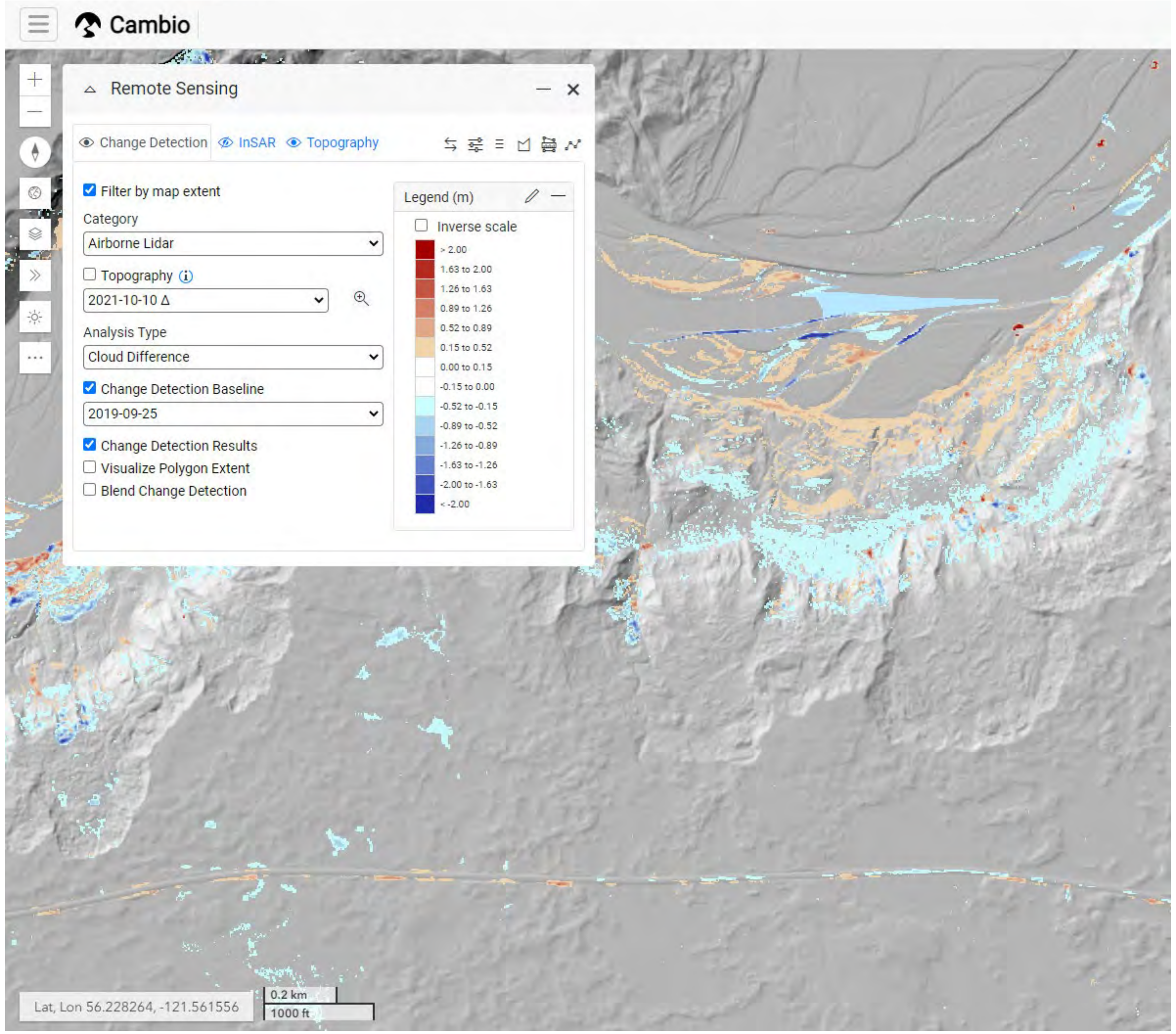



LANDSLIDES
Cedar River

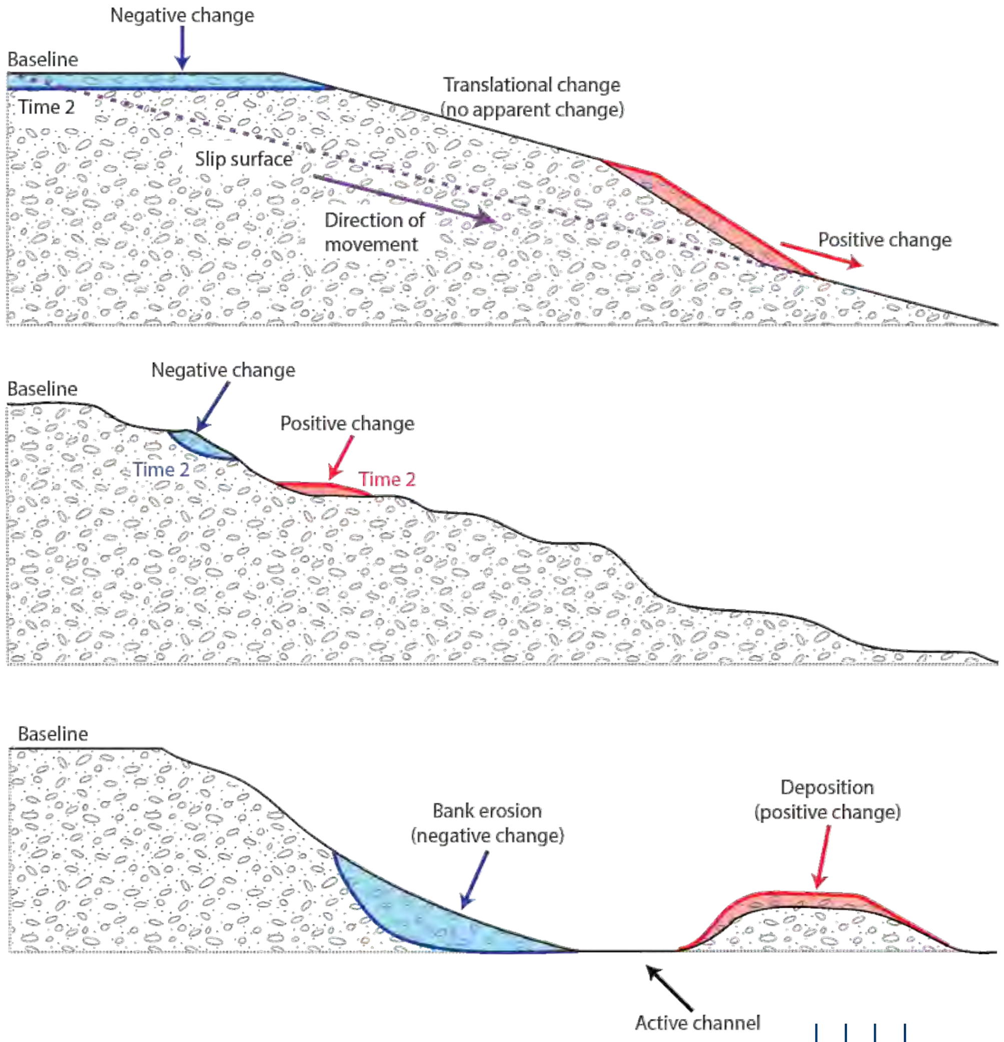

DEVILS SLIDE
Whatcom County


LANDSLIDE
Whatcom County

What can we do with it?



Lidar Change Detection



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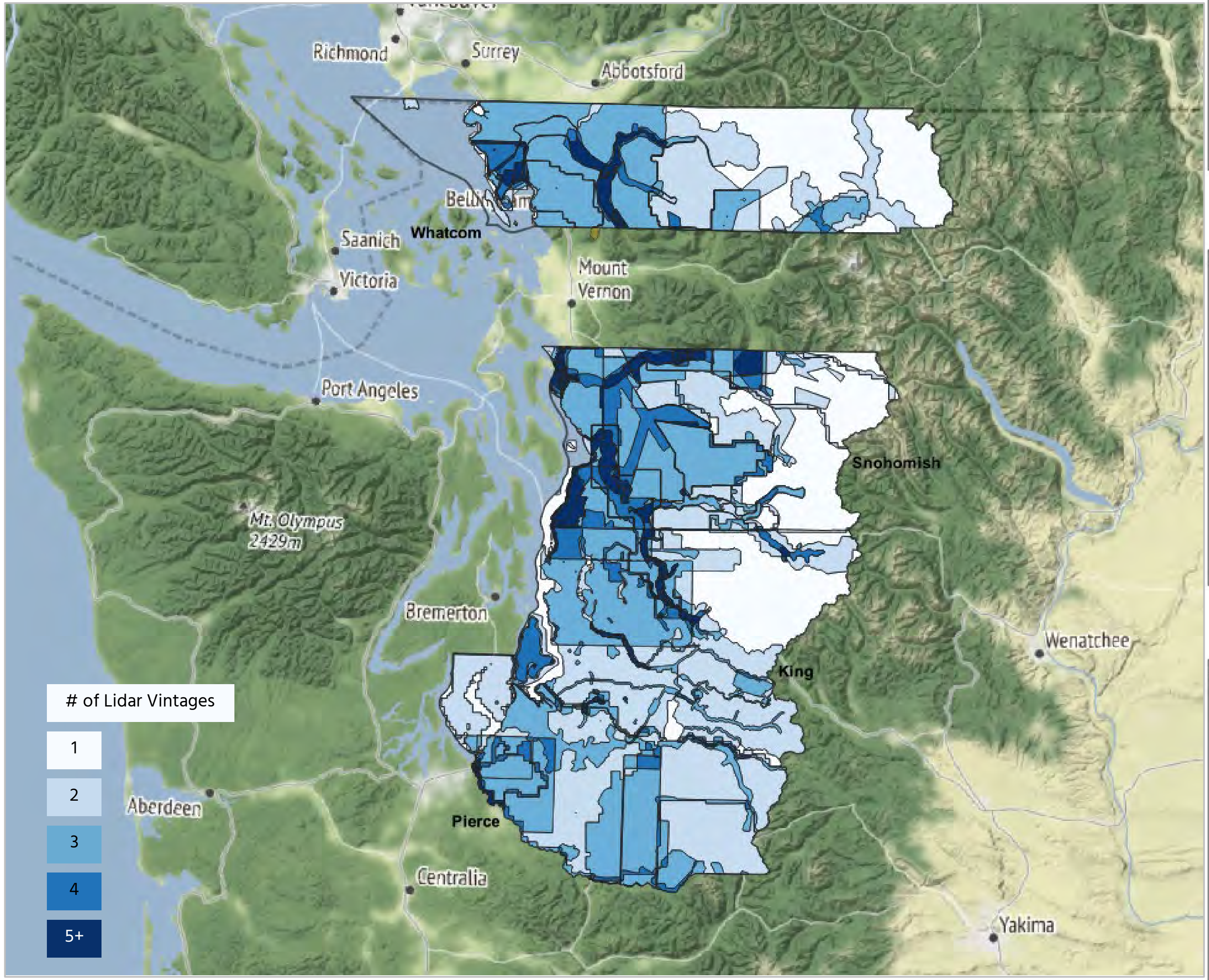
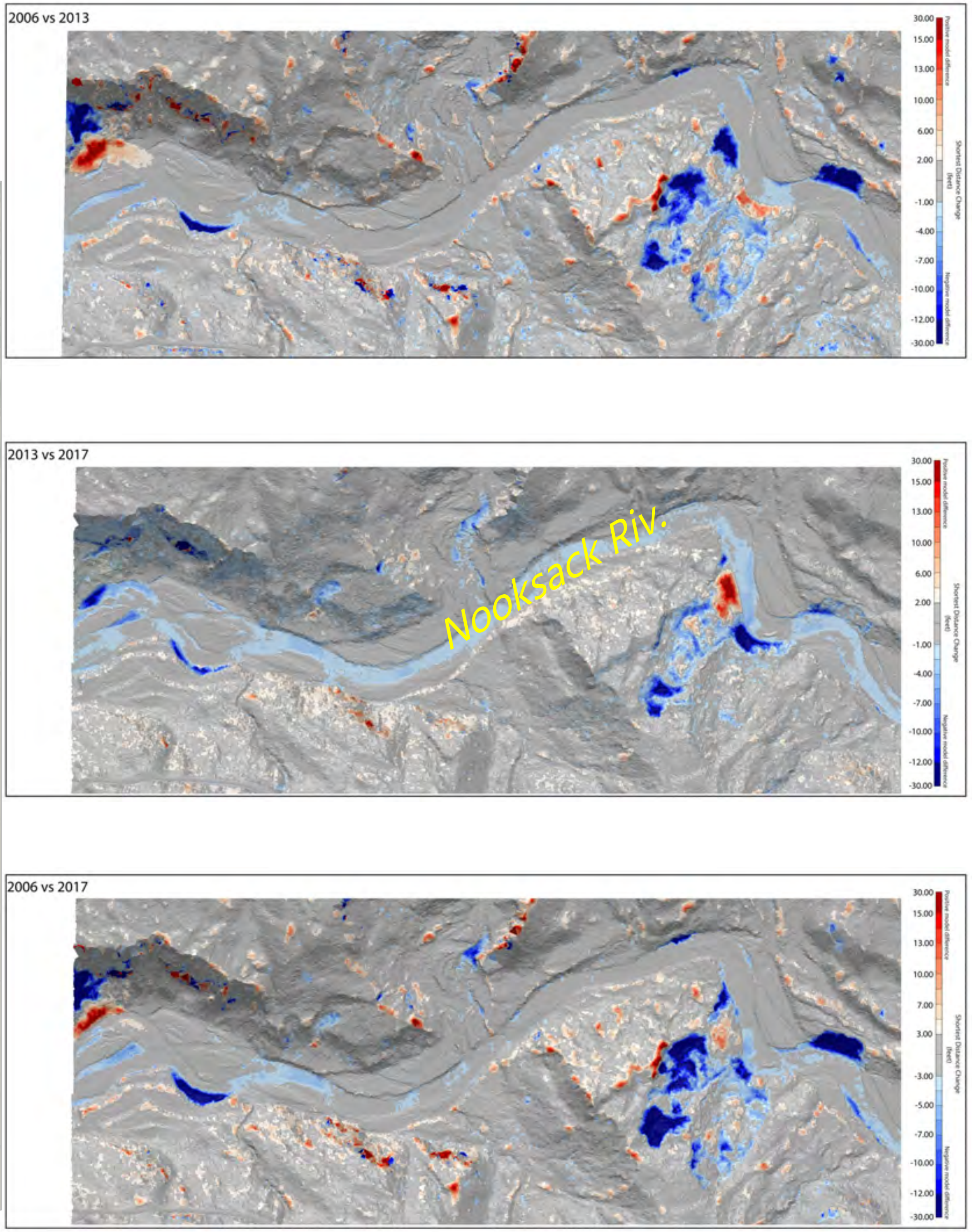
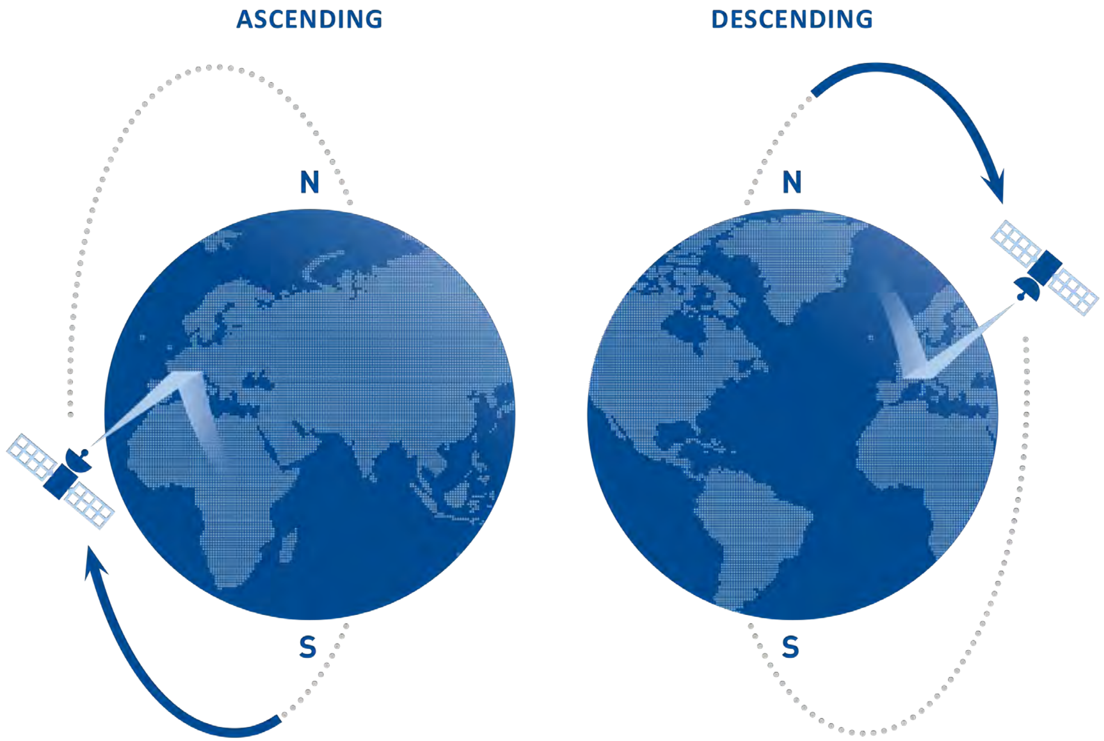
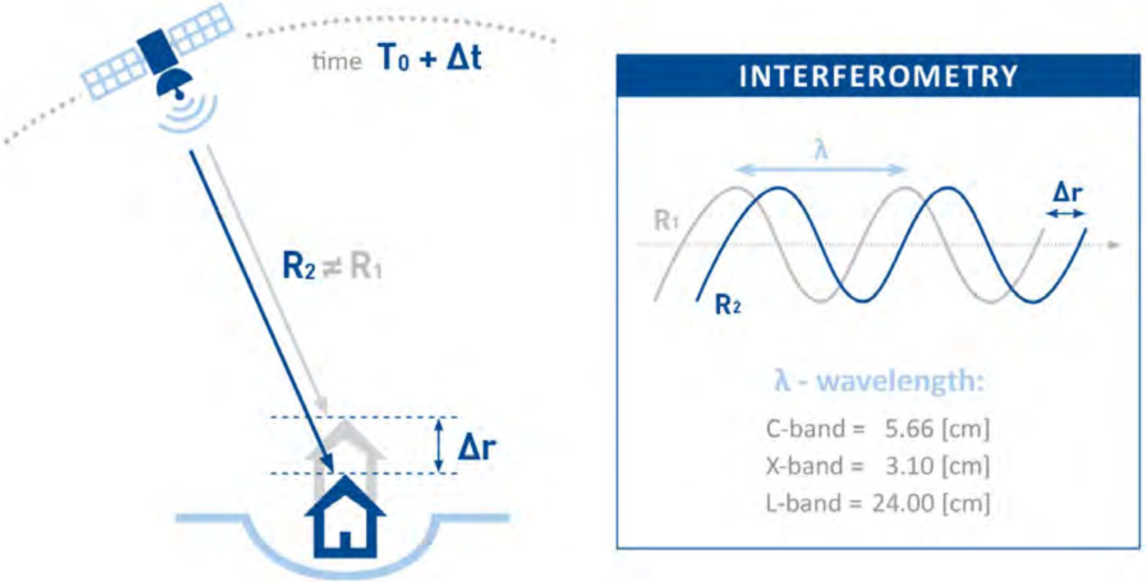
Lidar coverage and POC



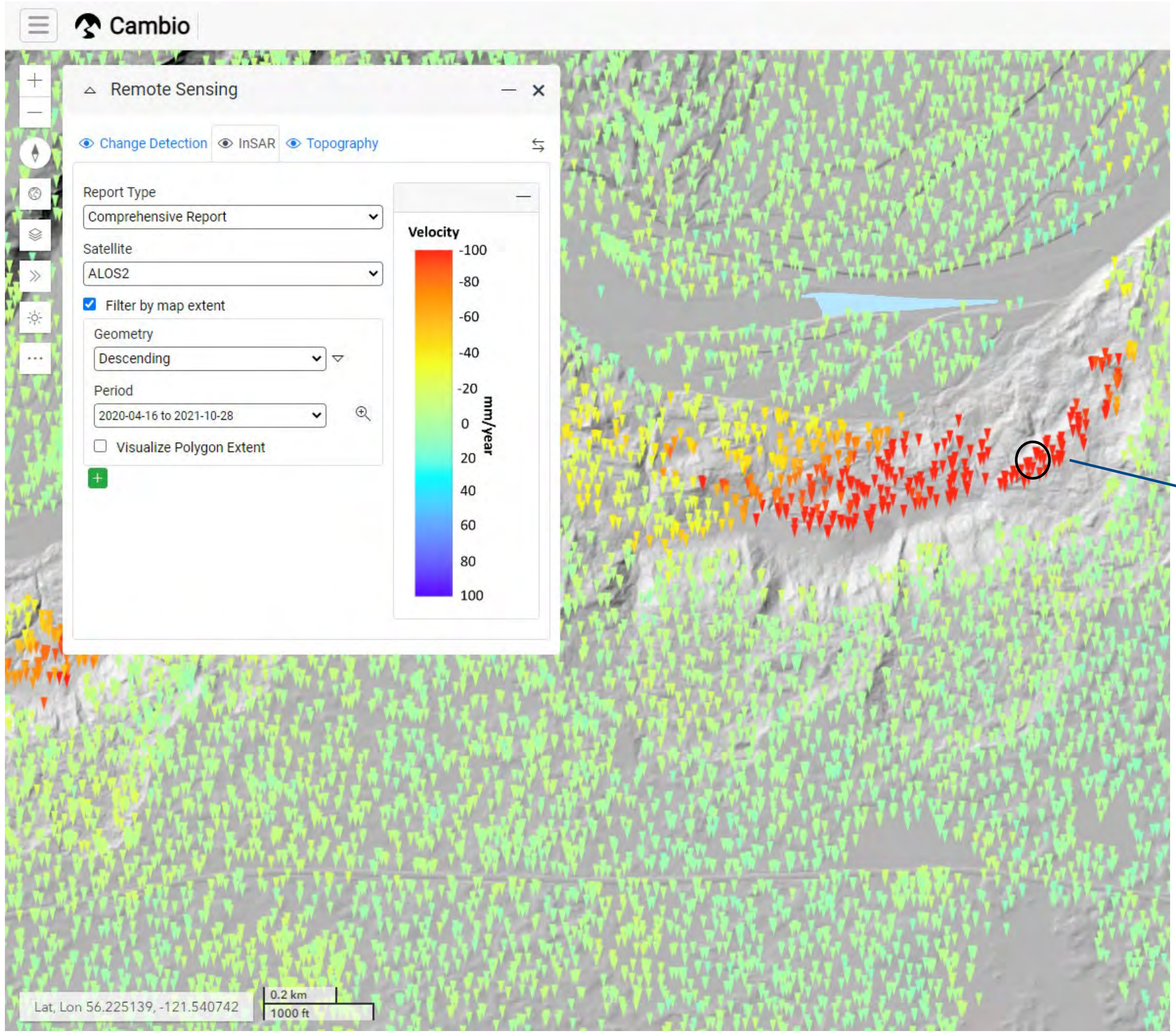


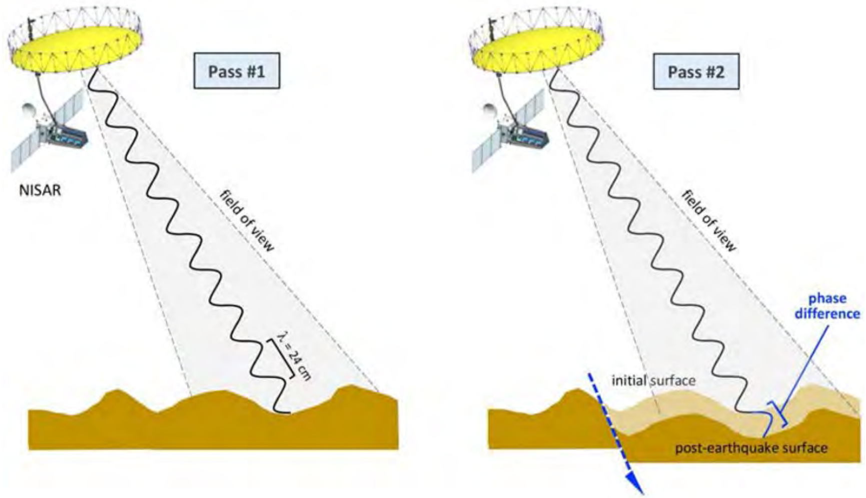
InSAR Analysis – InSAR Overview

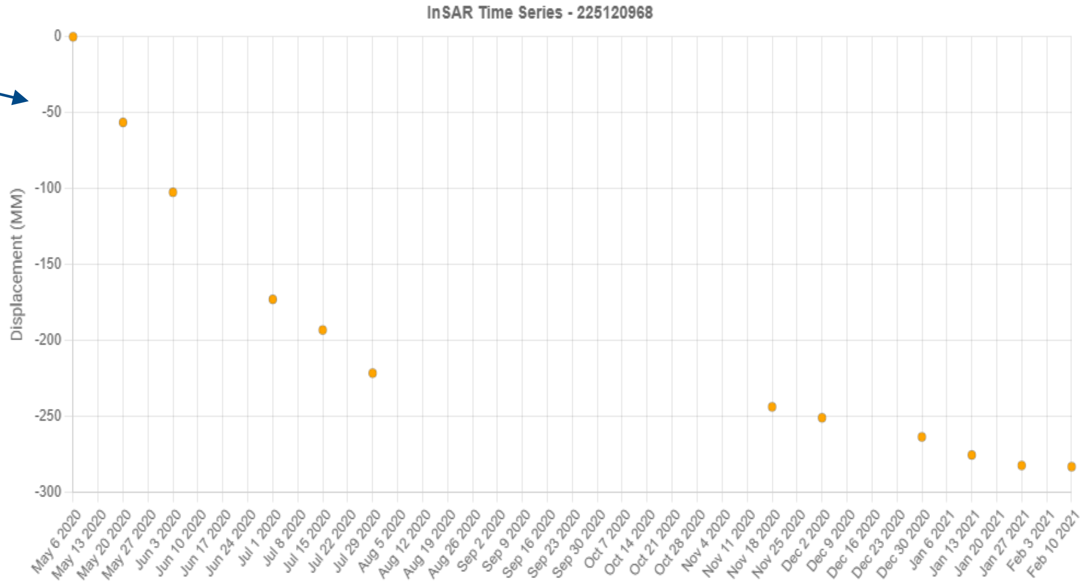




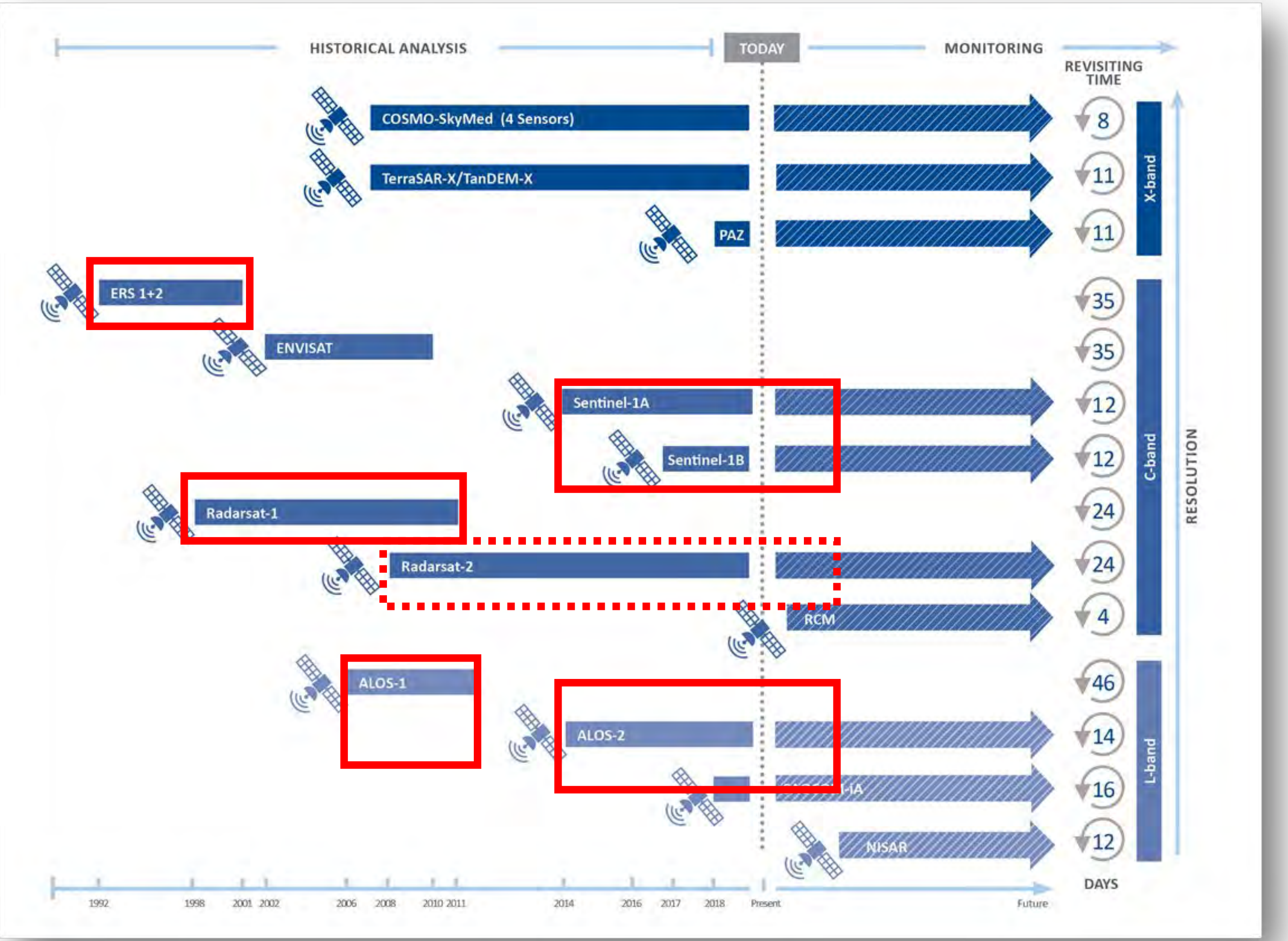
What can we do with it?







Available SAR Satellites

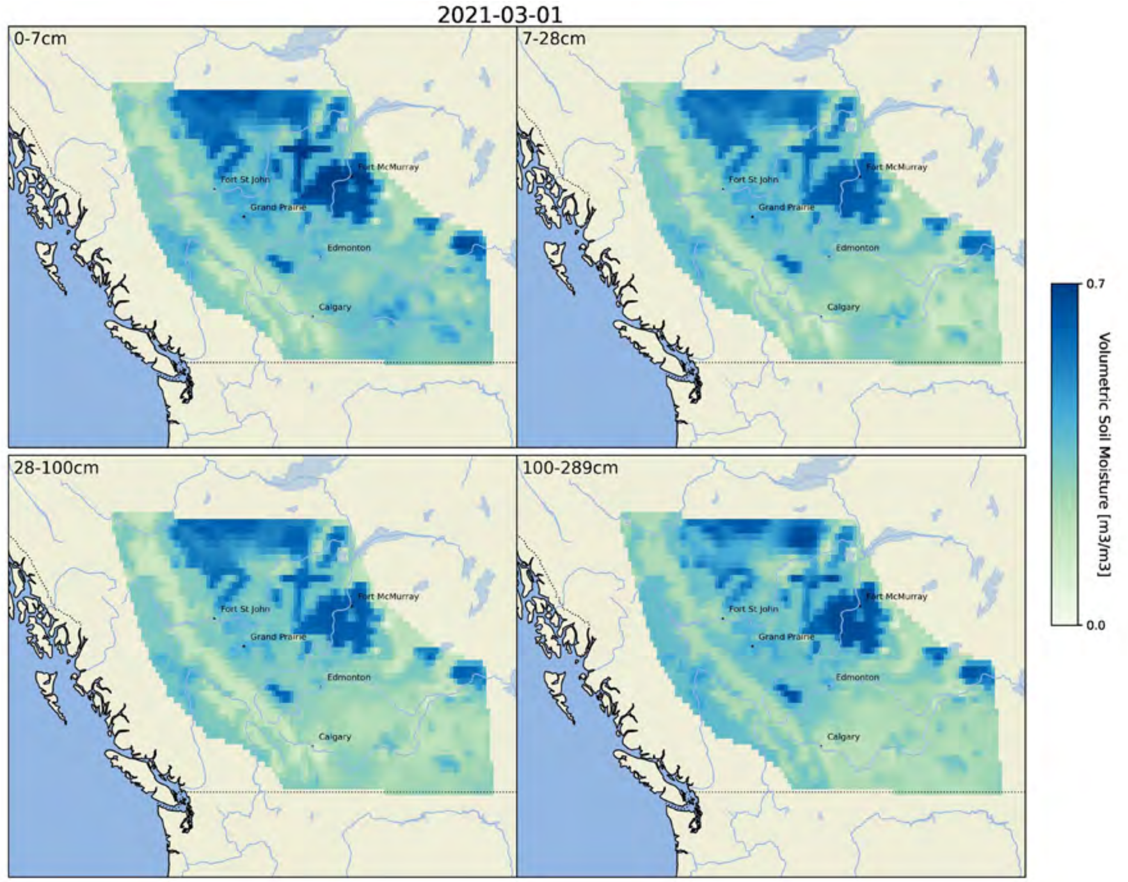


- **Satellites with SAR sensors have been collecting data as far back as 1992**
- **Washington State is DATA RICH**
- **Deep stacks back to:**
  - C-Band – 1992
  - L-Band - 2006

Objective 3

Understanding Kinematics

To develop causal mechanism hypotheses for individual landslides evaluated in the field. These mechanisms might include hydrogeologic characteristics visible in active landslides.



- Key reference sites (existing) obtained from:
  - Literature
  - Government files
  - Miller 2016/2017 reviews
  - InSAR

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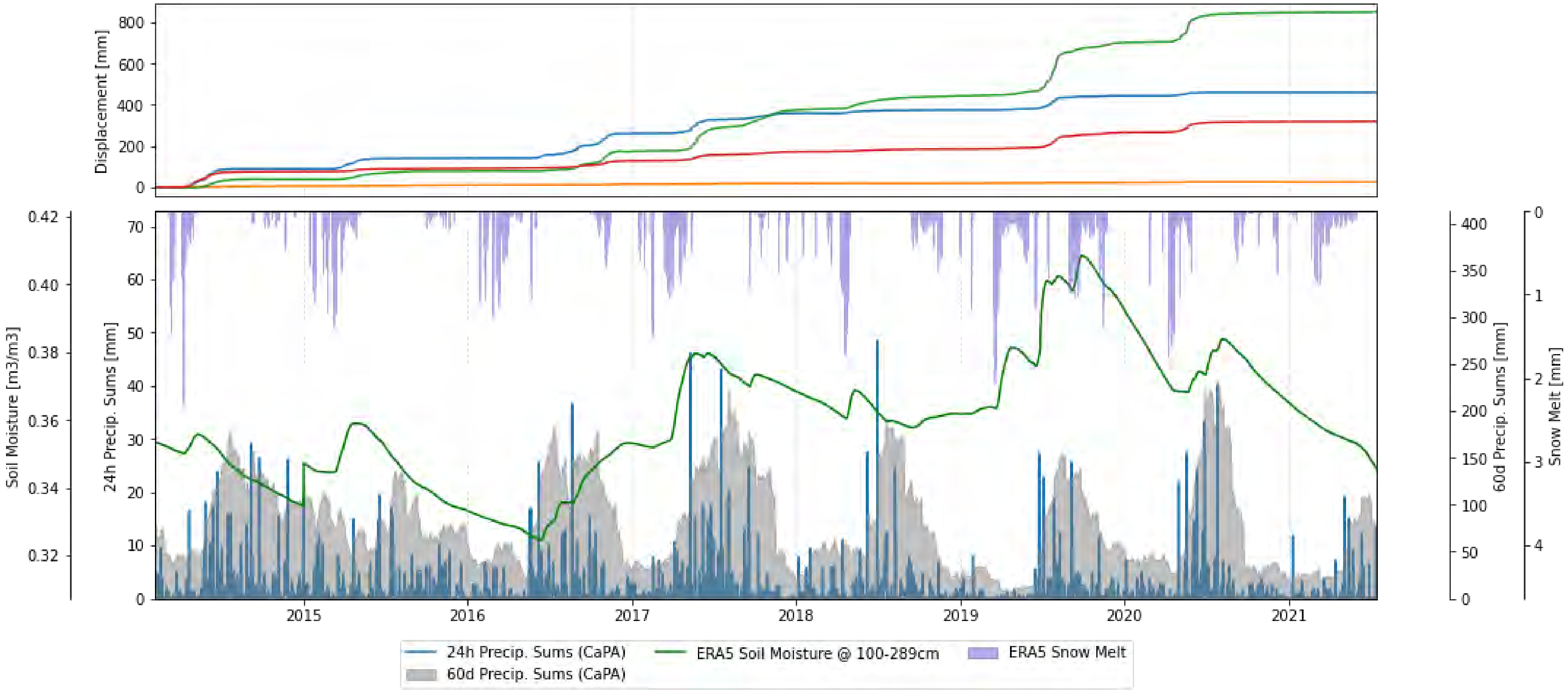

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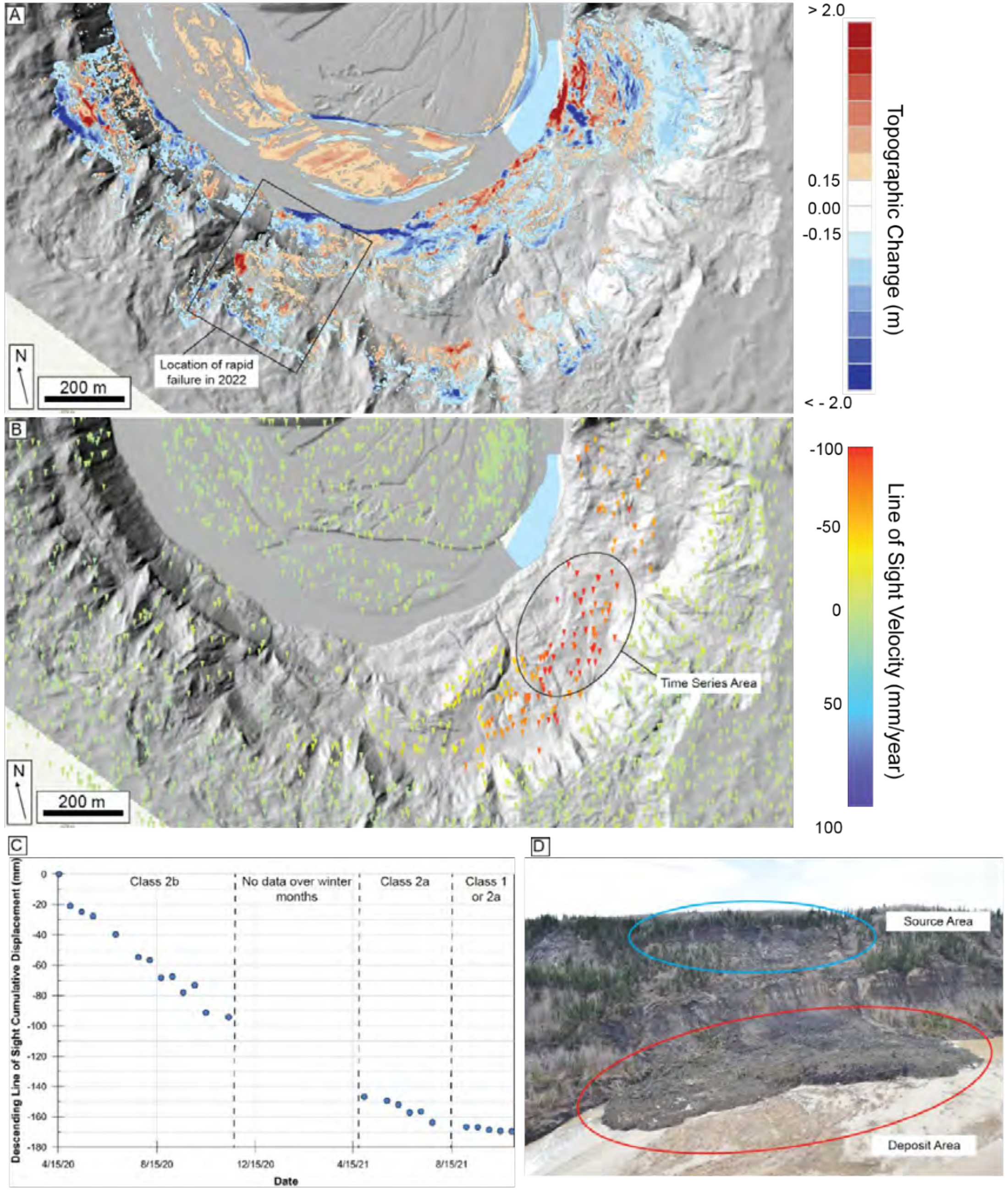
Objective 4

Remote Sensing Tool Assessment

To determine the best remote sensing tools, field assessment and other methods to classify DSLs in a manner that will aid in our understanding of the greater or lesser potential for DSL reactivation or accelerated movement.

- Data Coverages in relation to mapped landslides
- Measurement feasibility assessment



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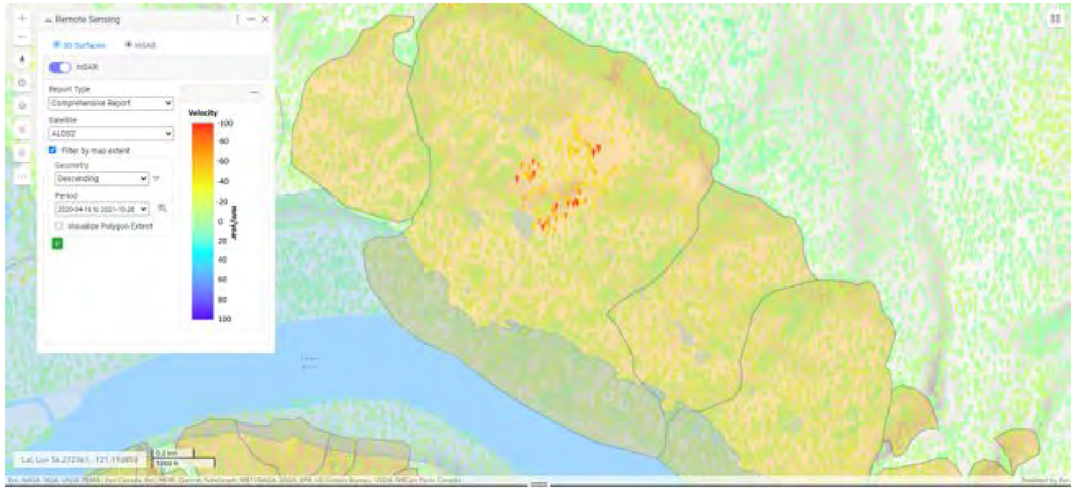
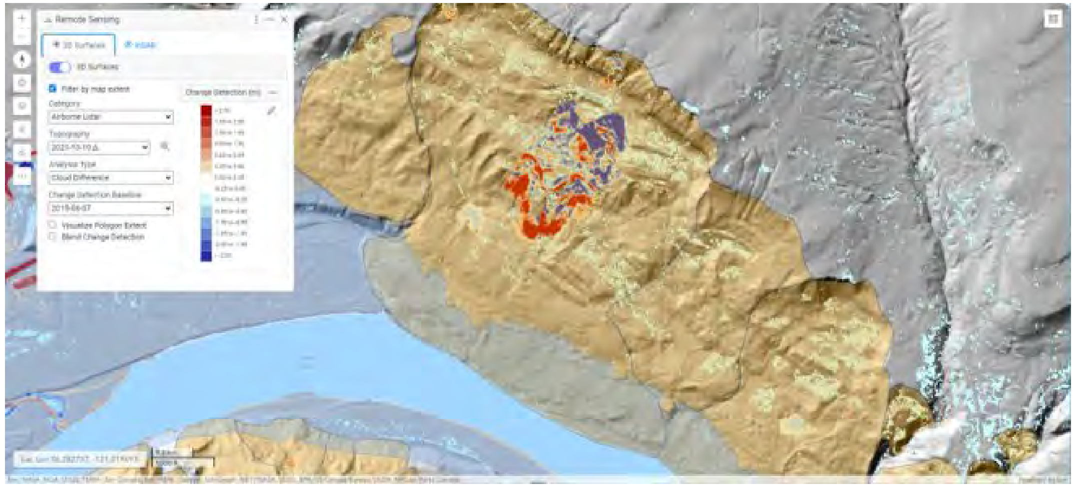
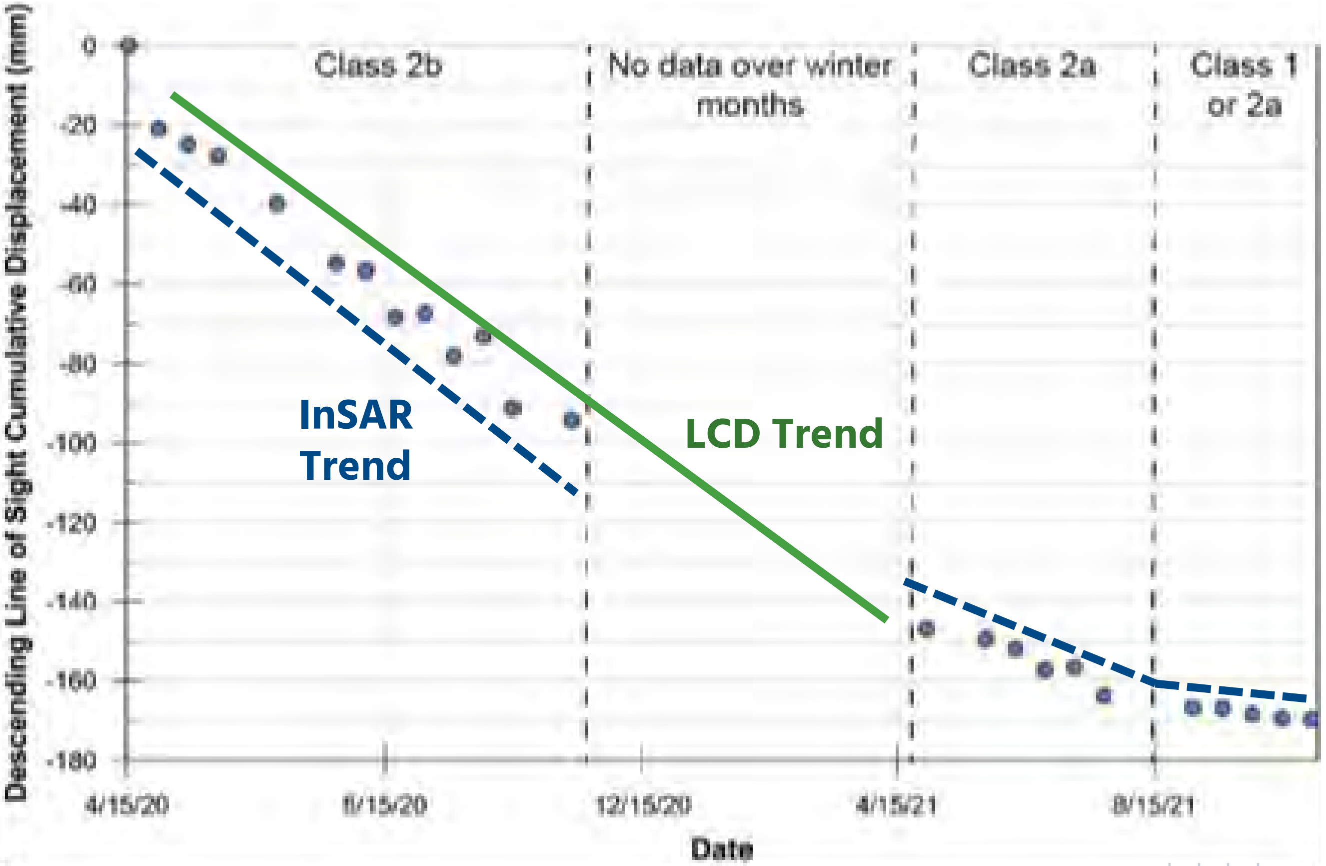
Combining Lidar and InSAR

Understanding Imaging Geometries and Measurements







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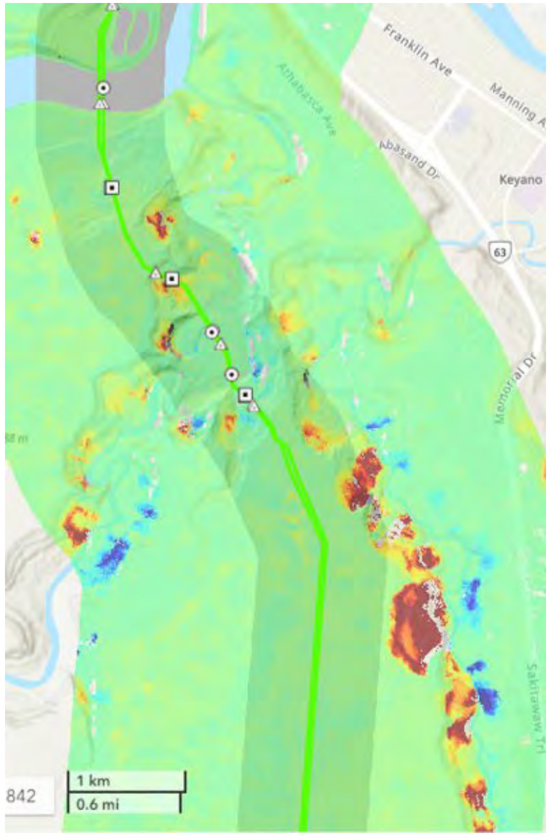
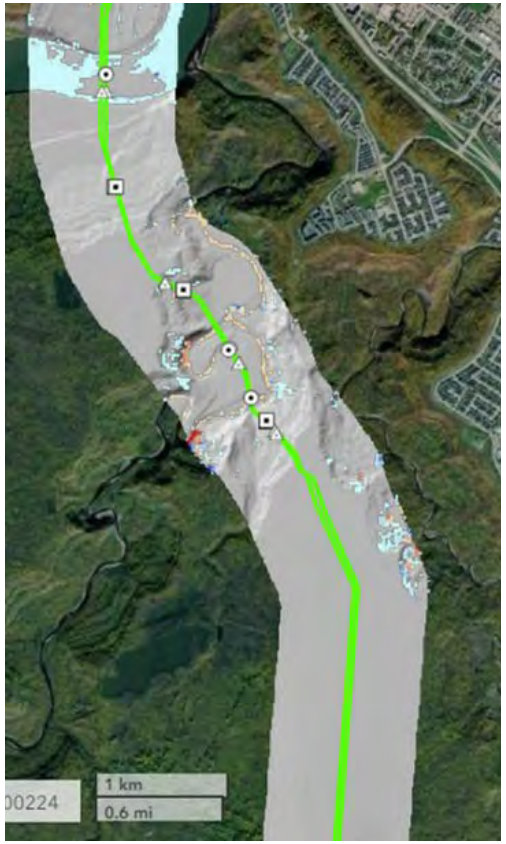
Objective 5

Defining Clusters and Characteristics

Building an Activity Inventory

To define classes of DSLs within and across clusters using a suite of physical attributes based on critical independent variables. These classes will also be used to support future phases of the research strategy (i.e.., which DSLs are most representative or illustrative for future research and modeling efforts based on the results of the classification project).



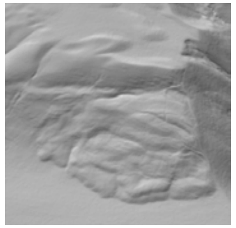
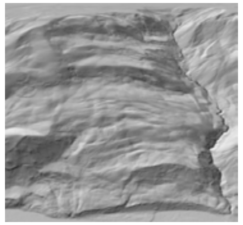
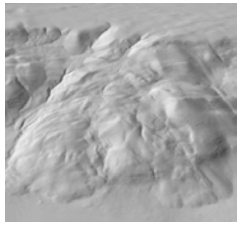
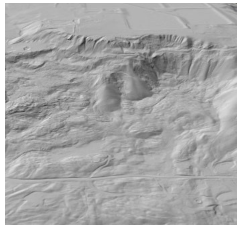
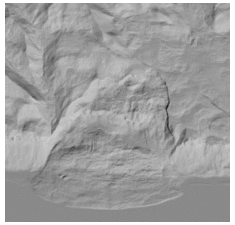


Morphological Characterization

To aid in predicting landslide velocity probability distributions and sensitivity to disturbance

Considerations

- Geology
- Failure mechanisms
- Slope Angle
- Slope Aspect
- Surface Roughness
- Depth to Rupture Surface
- Topographic Position
- Toe Condition
- Human Ground Modification
- Typical Velocity Class Distributions

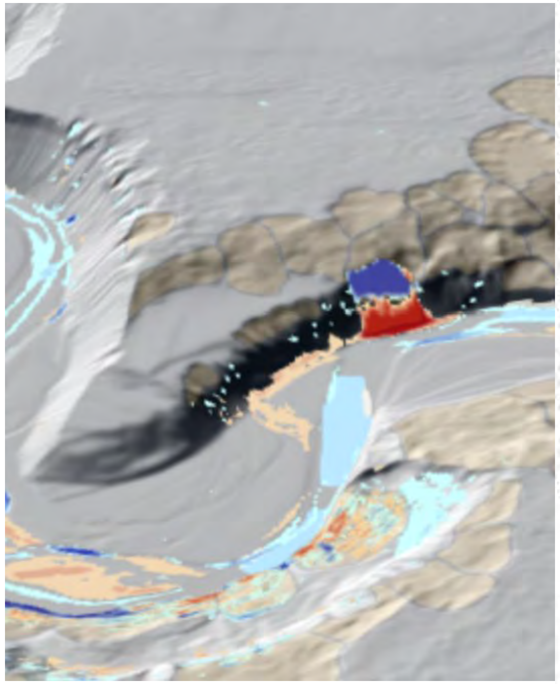
Behaviour Type	Type A	Type B	Type C	Type D	Type E
Typical geology	Relatively intact shales, mudstones	Relatively intact shales, mudstones, residual soils, overconsolidated glacial deposits	Relatively intact glacial deposits, colluvium derived from shales, mudstones, residual soil and glacial deposits	Colluvium derived from shales, mudstones, residual soil and glacial deposits	Colluvium derived from shales, mudstones, residual soil and glacial deposits
Typical failure mechanism	Translational block slides and spreads	Translational block slides and spreads	Translational block slides and spreads, rotational slides, complex earth slides-earth flows	Translational slides, rotational slides, earth flows, complex earth slides-earth flows	Translational slides, rotational slides, earth flows, complex earth slides-earth flows
Typical inclination of basal shear surface	Sub-horizontal (0 to 5 degrees)	Sub-horizontal (0 to 5 degrees)	Similar to the residual friction angle	Similar to the residual friction angle	Sub-parallel to the ground surface
Typical toe condition	No toe erosion	Toe erosion usually absent	Toe erosion may be active	Toe erosion often active	Toe erosion almost always active
Long-term annual probability of Class 4+ velocities	1 in 20,000	1 in 6,500	1 in 2,000	1 in 650	1 in 200
Assumed limiting state velocity class distribution; (assumed average annual displacement for each velocity class in brackets)					
0 (0 m) 1 (0.005 m) 2a (0.064 m) 2b (0.64 m) 3 (6.4 m) 4+ (64 m)	70% 28.5% 1.1% 0.4% 0.06% 0.005%	50% 45.5% 3.2% 1.1% 0.18% 0.015%	30% 55.0% 10.8% 3.6% 0.60% 0.050%	10% 44.9% 32.4% 10.8% 1.8% 0.15%	0.5% 3.0% 54% 36% 6.0% 0.50%
Mean annual displacement	0.01 m	0.03 m	0.1 m	0.3 m	1.0 m

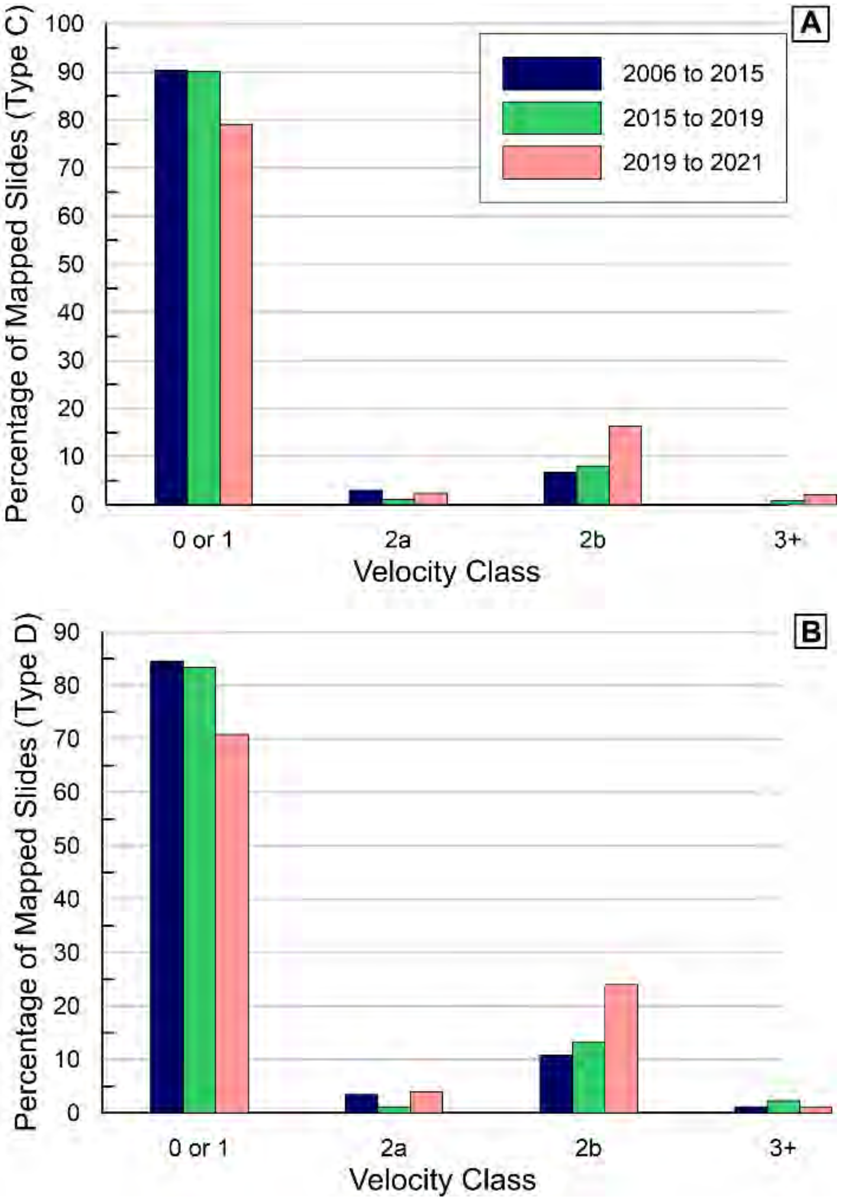
Activity Characterization

What trends can be identified over time that help constrain clusters?

Activity Trends to Delineate

- No measurable displacements (Class 0)
- Measurable displacements with no trend information (Class unknown)
- Consistent rates of movement (linear) (Class 1-3)
- Seasonal displacement changes observed (Class 1-3)
- Decadal/multi-year displacement trends observed (Class 1-4?)
- Sudden movements associated with external factors (Class 4+)





Data Access / Management

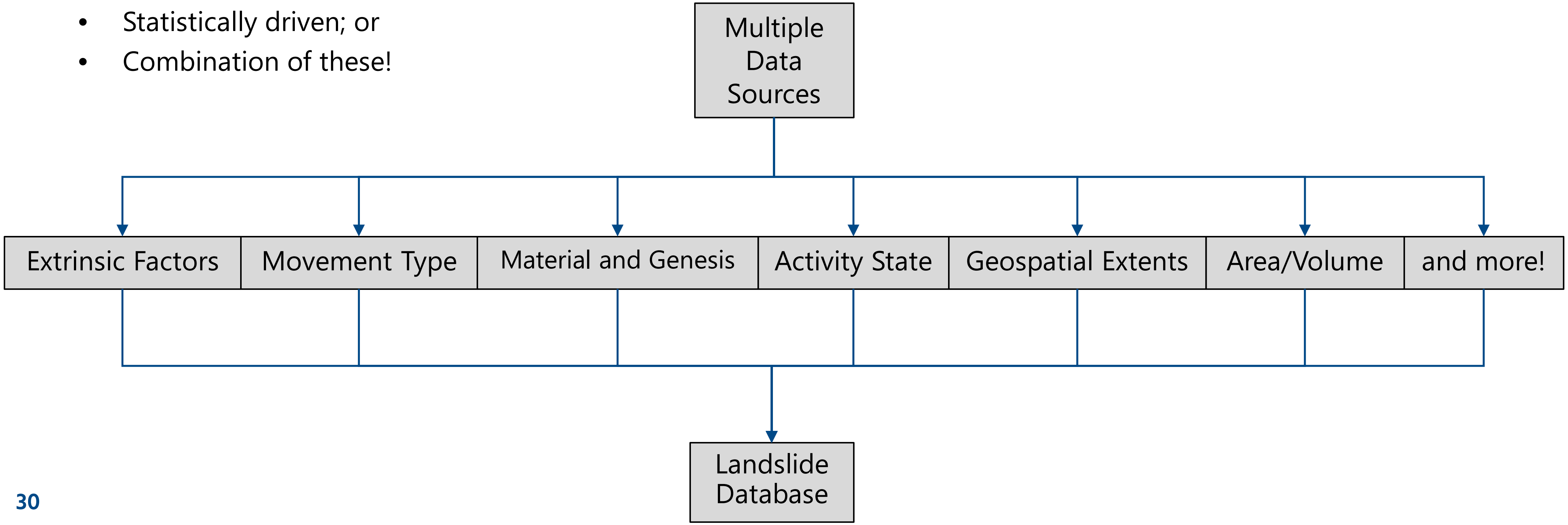
Starting on the right foot

Planning for the long term

- The challenge with disparate datasets

Future modeling efforts

- Physically based; or
- Statistically driven; or
- Combination of these!

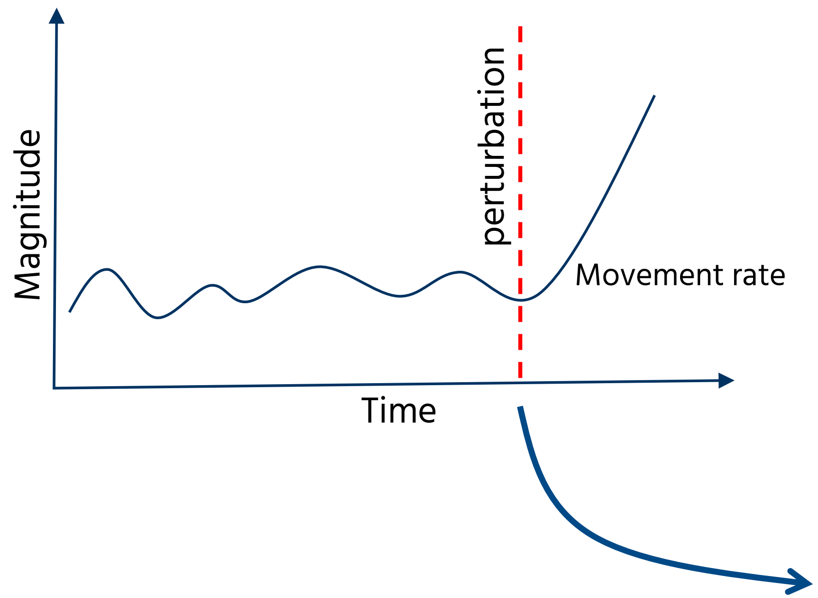


Objective 6

Defining Activity Transition Sensitivity

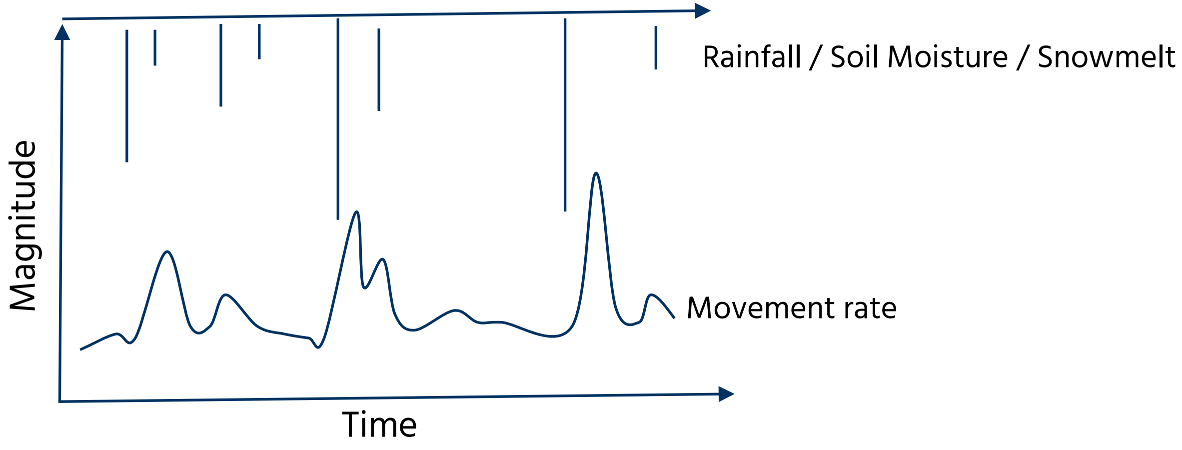
To initially hypothesize if certain classes of landslides have a particularly high or low potential for instability from forest practices and rank classes based on multiple sources of empirical evidence.

A landscape perturbation triggers a new phase of movement



Fire
Forestry Operations
Storms/Rain
Snowmelt
Loading
Development

Cyclicity of conditions drives movement



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Limitations

Unknowns and Unknown unknowns

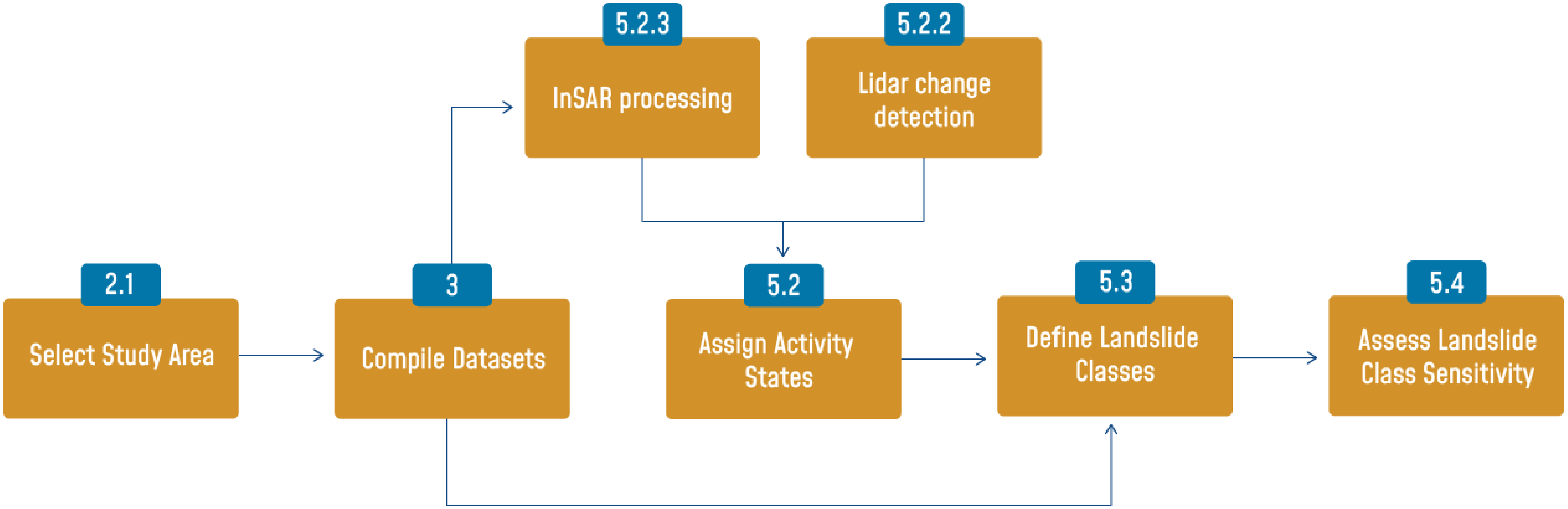
Considerations:

- The design is predicated on the **identification of velocity transitions** (e.g., landslides accelerating)
  - If too few transitions are identified, developing sensitivity estimates will be challenging
- **Scale**
  - Even field studies of single landslides are fraught with nuance (e.g., hydrogeology, landslide history)
  - We are aiming to provide screening level estimates on many thousands of landslides for use by DNR
- **Study not complete yet**
  - Proof of Concept
  - Can't predict the future – what will the initial data investigation uncover?

Summary of Program Design

Program Design in One Slide

Workflow designed to define landslide classes and estimate landslide class sensitivity



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Targeting the Study Design

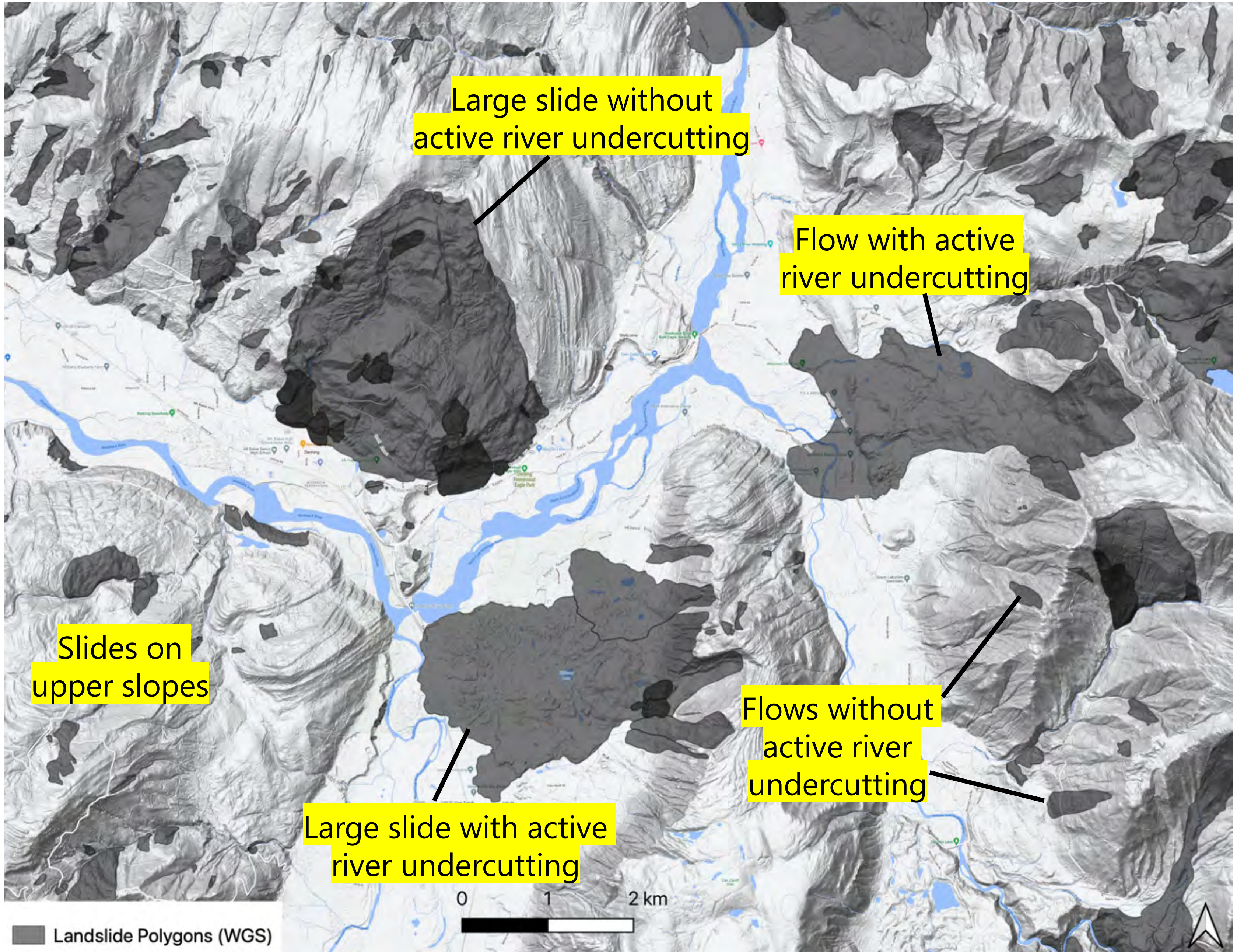
All about balance!

For a statistically robust dataset, evaluate areas with landslides initiating in different:

- Types of materials (e.g., igneous, metamorphic, glacial)
- Landscape positions (e.g., upper slopes, river valleys)
- Processes (e.g., flows, slides)
- Big and small

Also consider data depth!

- Are there enough data to develop statistically robust relationships?

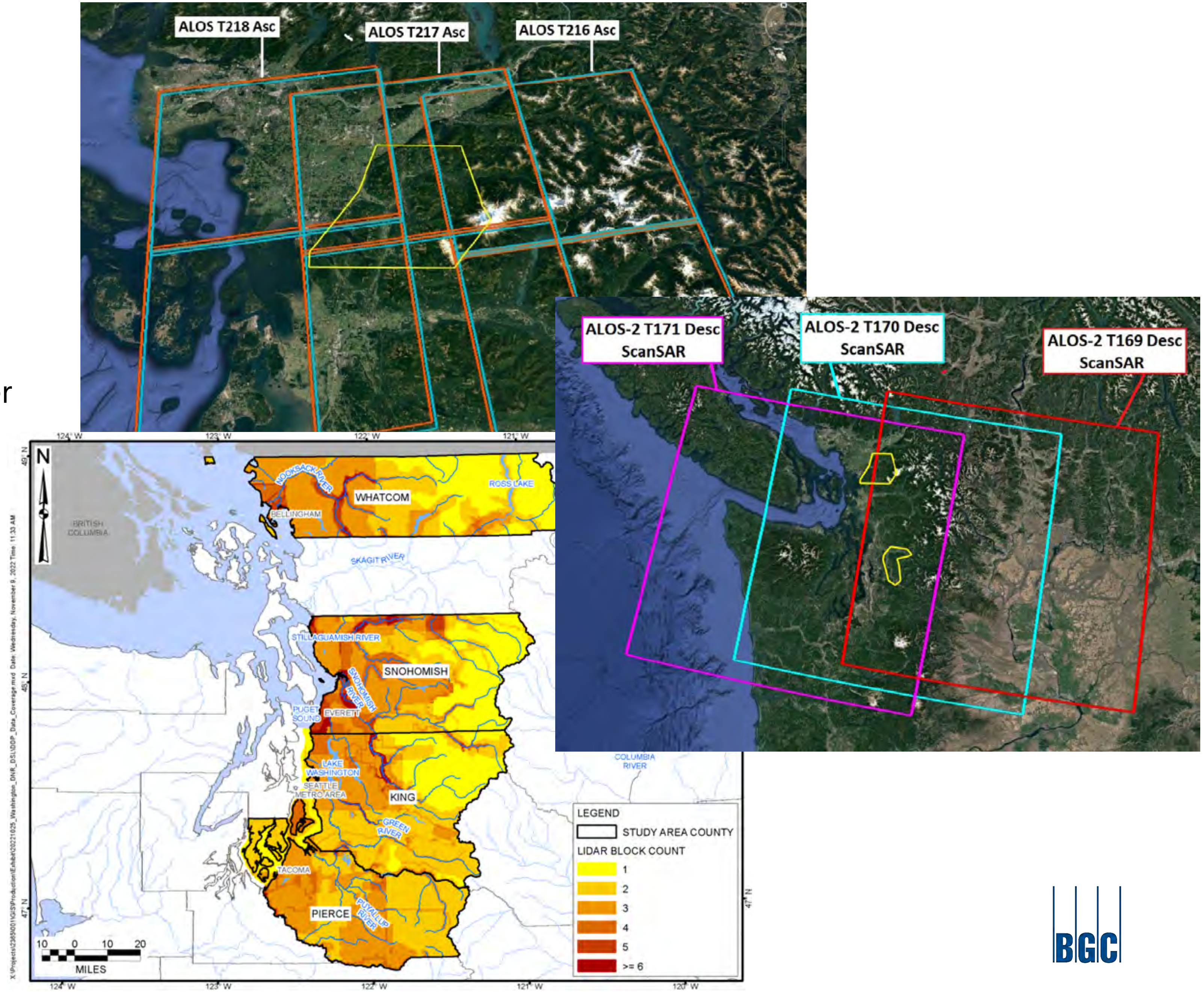


Targeting the Study Design

Historic Displacement Data Coverage

Minimum Data Requirements

- Single epoch-epoch LCD comparison over study area
- 2007-2011 L-Band InSAR
  - ALOS-1 Ascending, Fine
- 2014-2022 L-Band InSAR
  - ALOS-2 Descending, ScanSAR
- Optional Add-ons:
  - 2017-2022 C-Band InSAR (Ascending and Descending) – 2D Motion
  - Additional LCD analyses



**Example study areas. To be refined with DNR

Targeting the Study Design

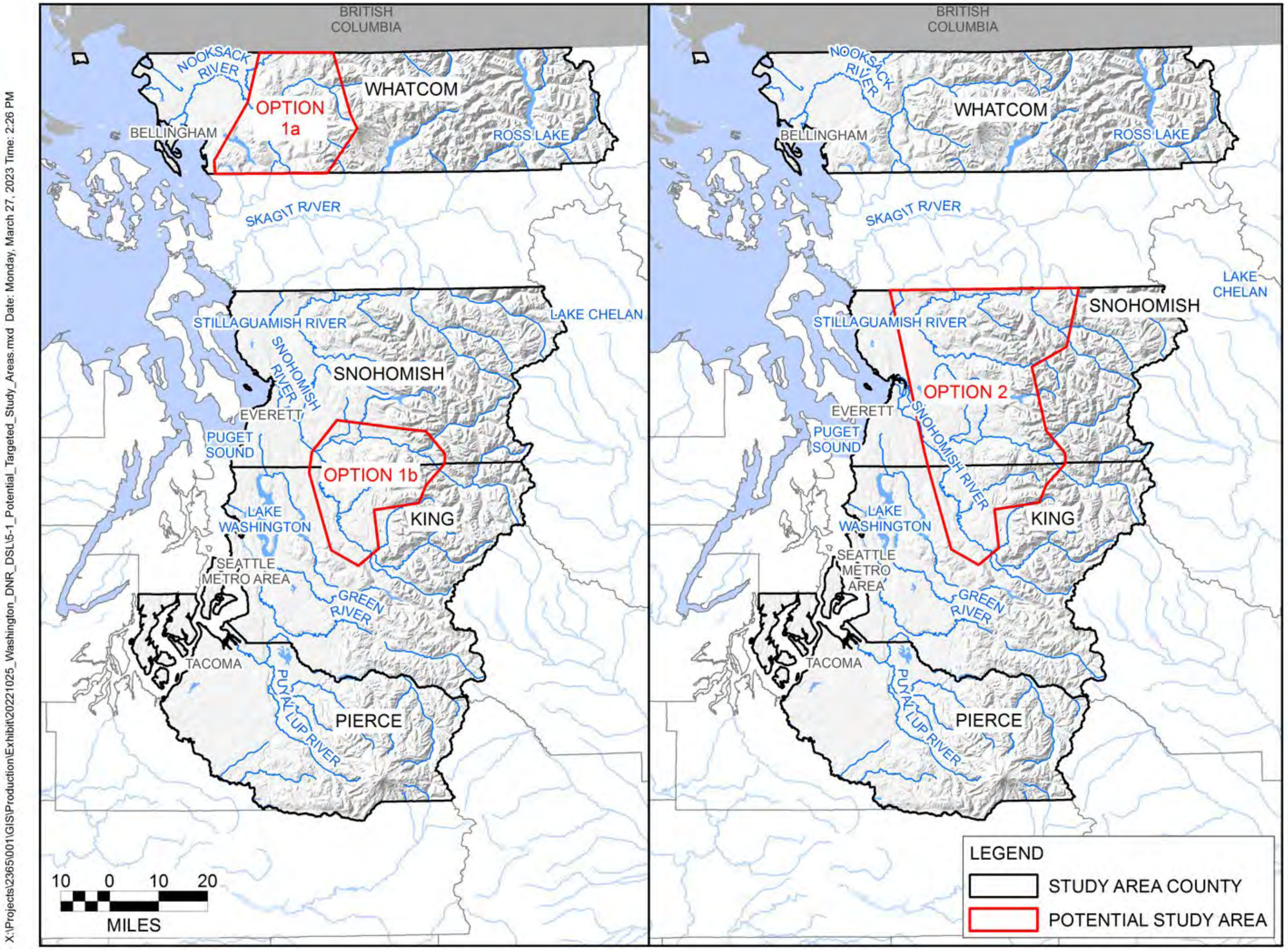
Balance areas of varied landslide processes, geology, and topography

Option 1: Western Whatcom County and the Upper Snohomish River System (Snoqualmie and Skykomish Rivers) – 2,700 km^2, >3,000 mapped DSLs

Option 2: Snohomish County (Sloan Peak to Snohomish) and the Snoqualmie River Valley (Fall City to Monroe) – 3,600 km^2, >4,350 mapped DSLs

For both:

- Up to 6 lidar acquisitions to date
- L-band SAR back to 2004



Expected Deliverables

Database, Workflow, the Architecture for Further Analytics

To Be Determined

- Methodology report
- Digital data transmittal
  - Database
  - Geospatial files – displacement data, landslide classes, types, clusters
- Direct input into:
  - Project 4.7 – GIS-Based Stability and Sensitivity Toolkit
  - Project 4.9 – Physical Modelling Project
  - Project 4.10 – Monitoring Project
  - Project 4.11 – Modeled Evapotranspiration Refinement Project

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Closing

This presentation required a number of complex issues to be reduced to general concepts in a series of concise bullet points, photographs, and/or diagrams. The content of this presentation is not intended for design decisions or construction. This presentation is for general informational purposes only. BGC Engineering Inc.'s report(s) may contain more specific details concerning the issues identified in this presentation. Please consult BGC for further clarification if you have any questions or concerns.

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