Solid Earth

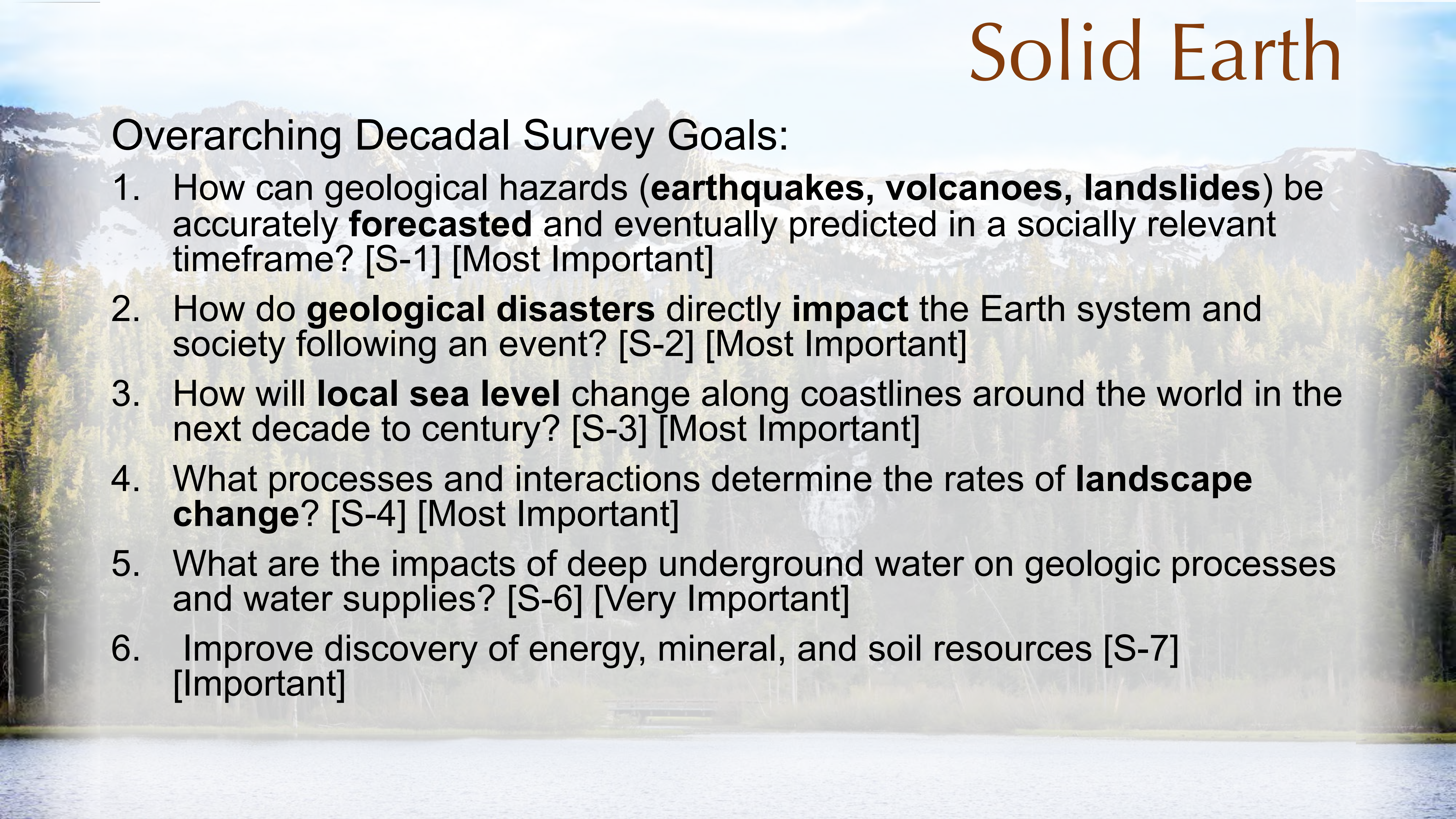
Paul Lundgren, JPL

- Earthquake, volcano and landslide assessment, response, mitigation and modeling
- Vertical land motion/relative sea level rise
- Tectonics/deposition/erosion/climate coupled processes
- Anthropogenic and natural change detection

Solid Earth

Overarching Decadal Survey Goals:

1. How can geological hazards (**earthquakes, volcanoes, landslides**) be accurately **forecasted** and eventually predicted in a socially relevant timeframe? [S-1] [Most Important]
2. How do **geological disasters** directly **impact** the Earth system and society following an event? [S-2] [Most Important]
3. How will **local sea level** change along coastlines around the world in the next decade to century? [S-3] [Most Important]
4. What processes and interactions determine the rates of **landscape change**? [S-4] [Most Important]
5. What are the impacts of deep underground water on geologic processes and water supplies? [S-6] [Very Important]
6. Improve discovery of energy, mineral, and soil resources [S-7] [Important]



DS Objectives

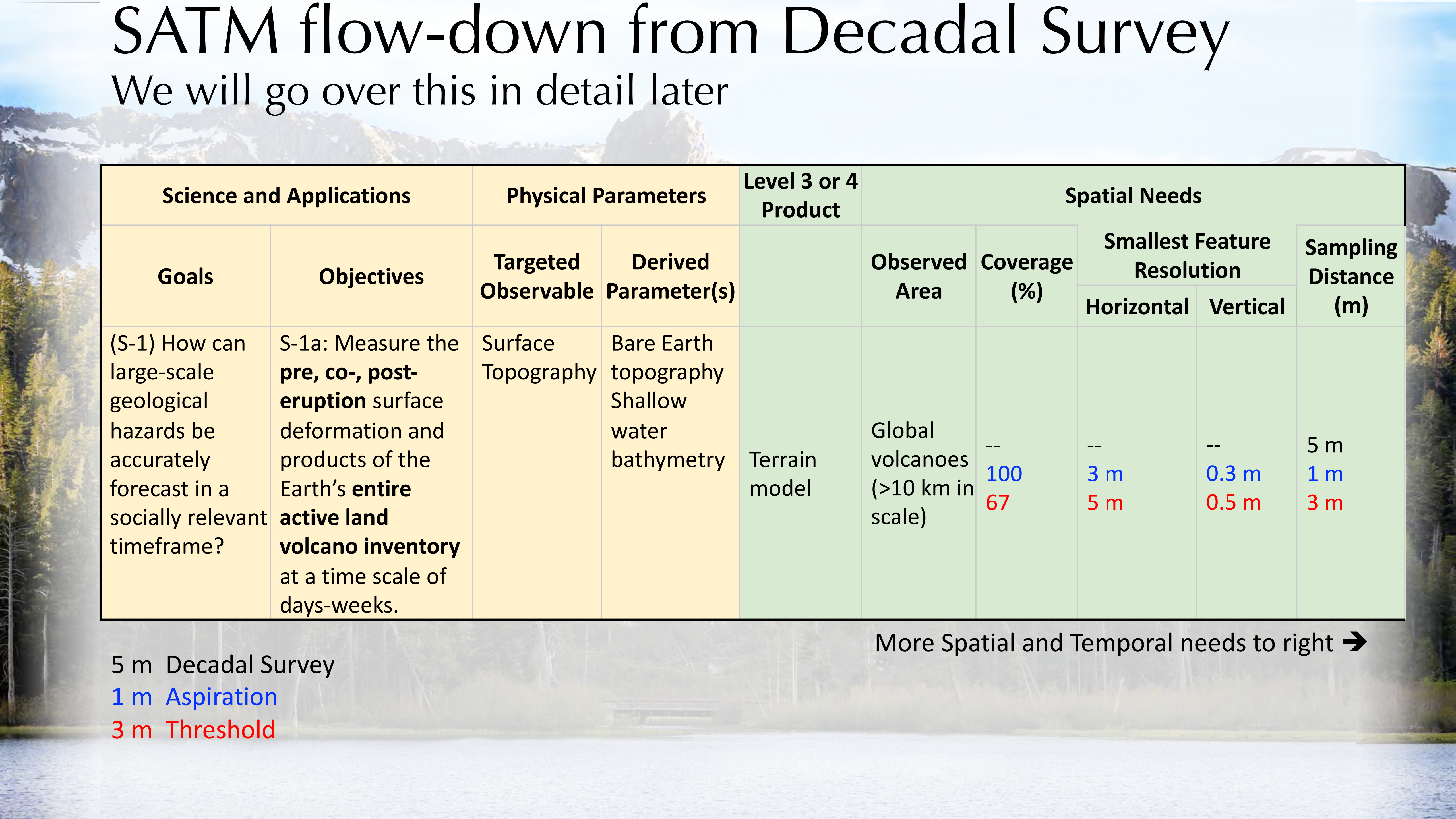
- **S-1a.** Measure the pre-, syn-, and post **eruption** surface deformation and **products** of Earth’s entire active land volcano inventory with a time scale of days to weeks
- **S-1b.** Measure and forecast inter-, pre-, co-, and post-**seismic** activity over tectonically active areas on time scales ranging from hours to decades
- **S-1c**. Forecast and monitor **landslides**, especially those near population centers
- **S-2a.** Rapidly capture the **transient** processes following disasters for improved predictive modeling, as well as response and mitigation through optimal retasking and analysis of space data
- **S-2b**. Assess surface deformation, extent of surface change…of **volcanic products** following a volcanic eruption (hourly to daily temporal sampling)
- **S-2c**. Assess co- and post-seismic ground deformation and **damage to infrastructure** following an earthquake

DS Objectives

- **S-3a**. Quantify the rates of sea-level change and its driving processes at global, regional, and local scales.
- **S-3b.** Determine **vertical motion** of land along coastlines.
- **S-4a.** Quantify global, decadal **landscape change** produced by abrupt events and by continuous reshaping of Earth’s surface due to surface processes, tectonics, and societal activity

SATM flow-down from Decadal Survey

We will go over this in detail later

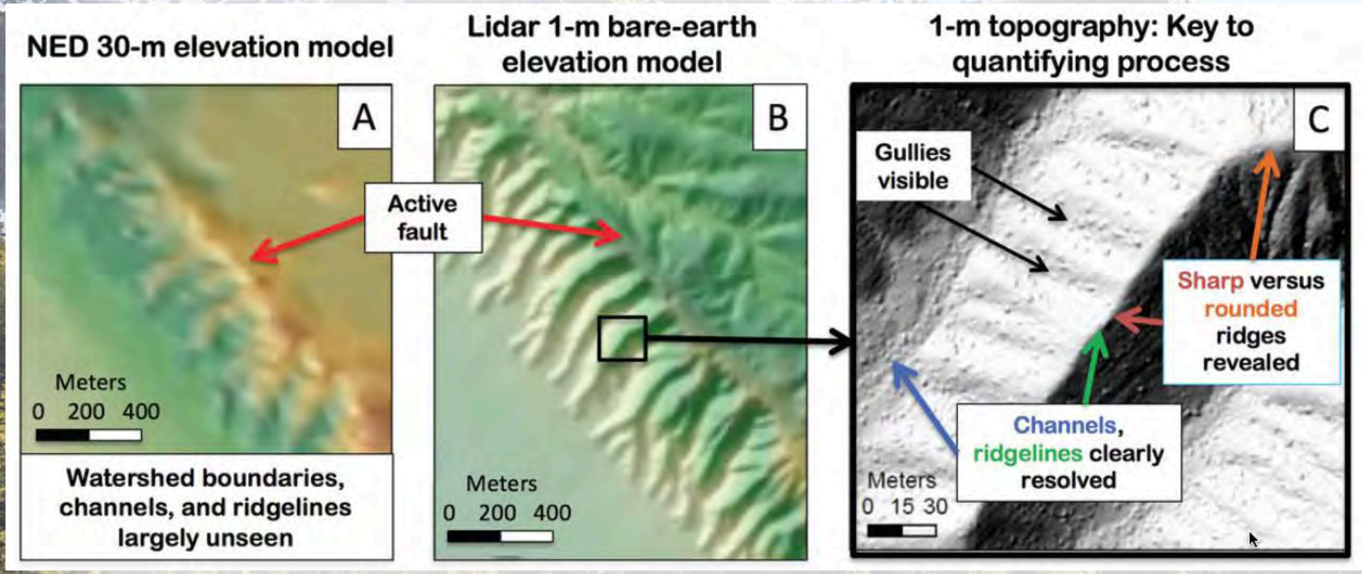


Science and Applications		Physical Parameters		Level 3 or 4 Product	Spatial Needs				
Goals	**Objectives**	**Targeted Observable**	**Derived Parameter(s)**		**Observed Area**	**Coverage (%)**	**Smallest Feature Resolution**		**Sampling Distance (m)**
							Horizontal	**Vertical**	
(S-1) How can large-scale geological hazards be accurately forecast in a socially relevant timeframe?	S-1a: Measure the **pre, co-, post-eruption** surface deformation and products of the Earth's **entire active land volcano inventory** at a time scale of days-weeks.	Surface Topography	Bare Earth topography Shallow water bathymetry	Terrain model	Global volcanoes (>10 km in scale)	-- 100 67	-- 3 m 5 m	-- 0.3 m 0.5 m	5 m 1 m 3 m

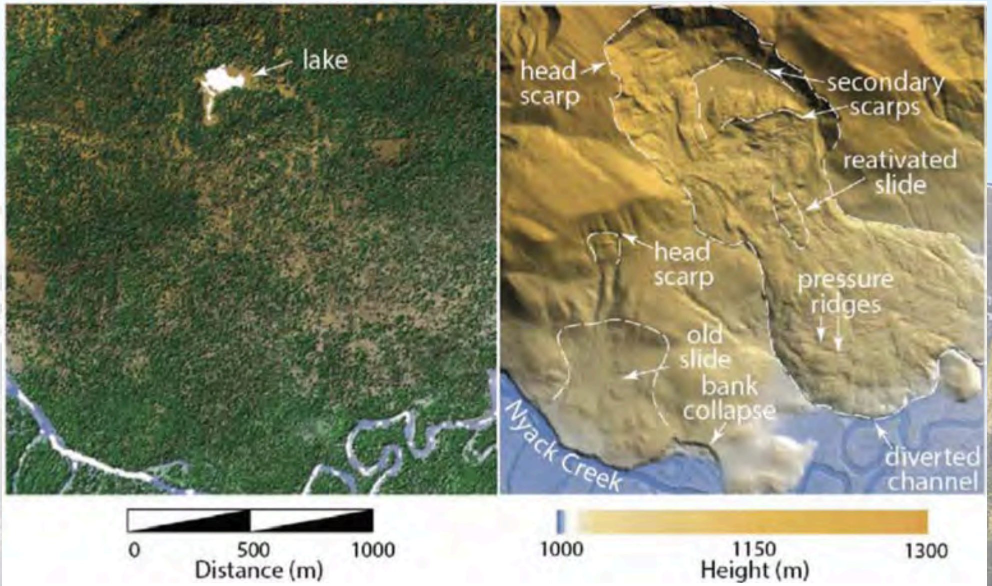
More Spatial and Temporal needs to right ➔

5 m Decadal Survey
1 m Aspiration
3 m Threshold

Static topography



Example of erosion and tectonics, Dragon's Back ridge near San Andreas fault, from Decadal Survey (2017), based off Hurst et al. (Science, 2013)



(Ramesh Shrestha and the National Center for Airborne Laser Mapping, NAS, Decadal Survey, 2017)

LIDAR (≤ 1 m) reveals landslides beneath forest

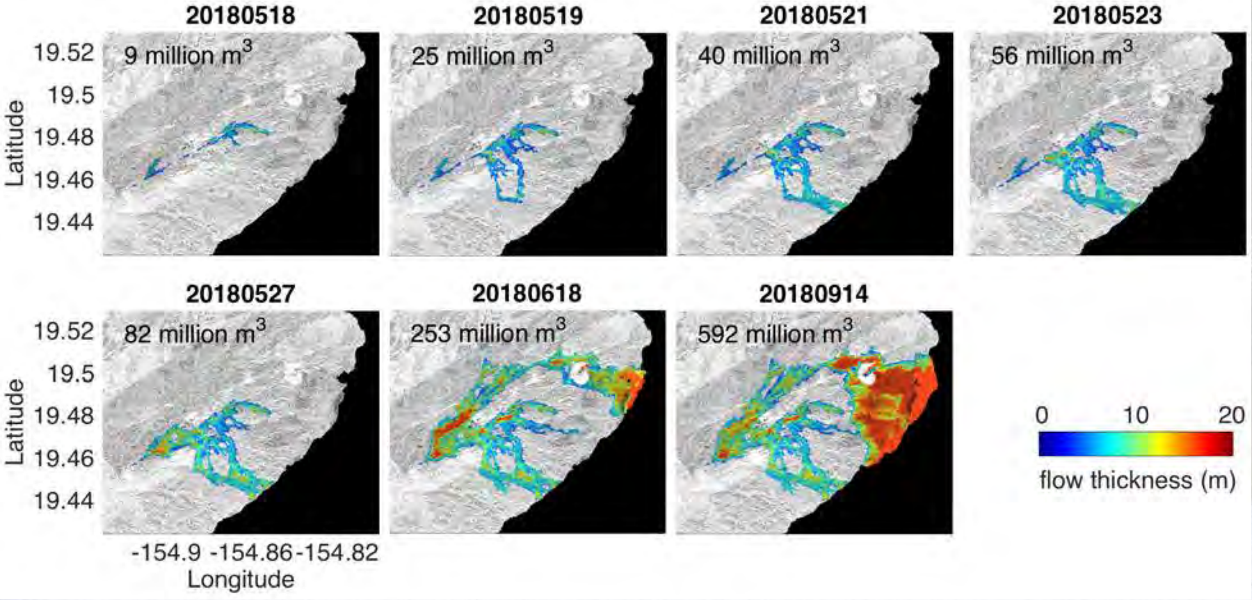
One-off or infrequent high resolution bare-earth topography needed for slow tectonic-climate characterization and to reveal the bare earth at high resolution for geomorphology analysis

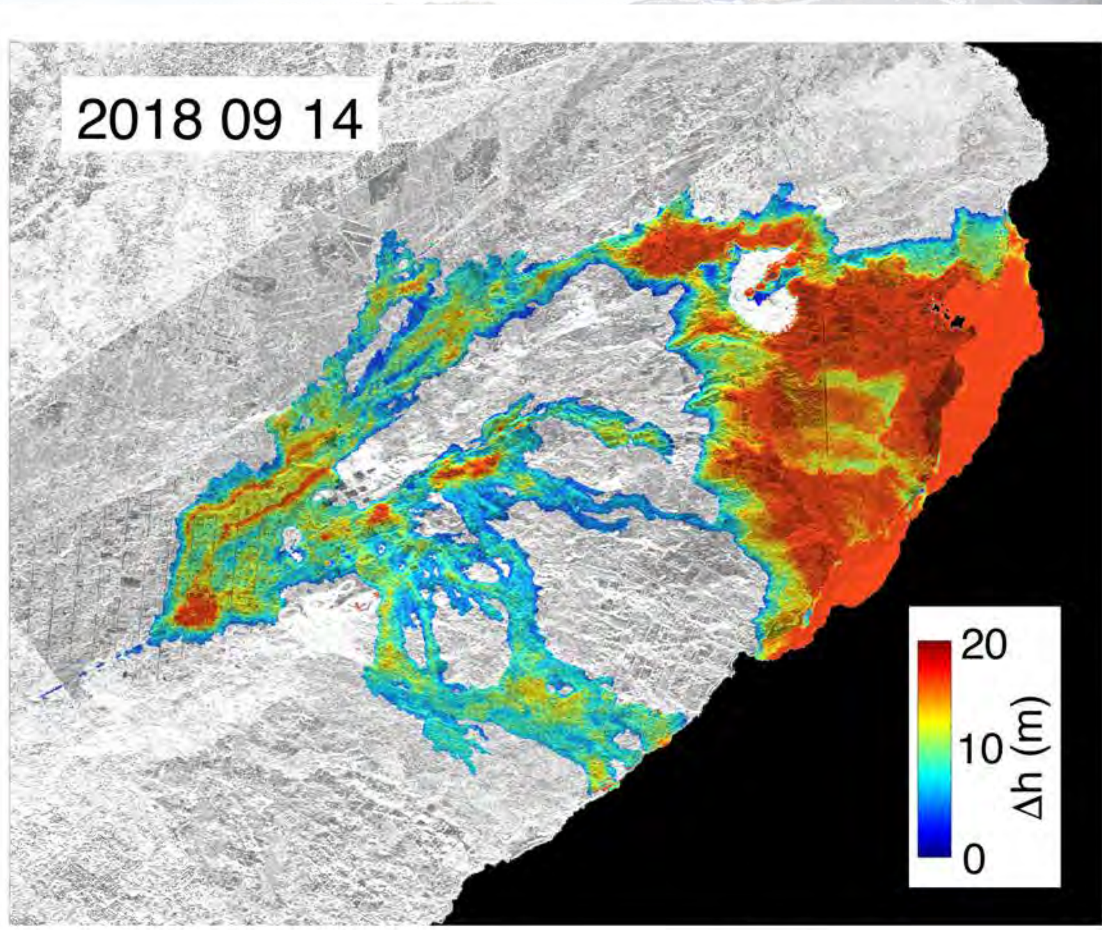
Time varying topo: Kilauea 2018 eruption

Differential topography using NASA GLISTIN-A SAR (3 m posting).

*Highlights need for **temporal** sampling, **spatial** coverage, and resolution.*

*Ok for **total volume**, but what about **dynamics?***

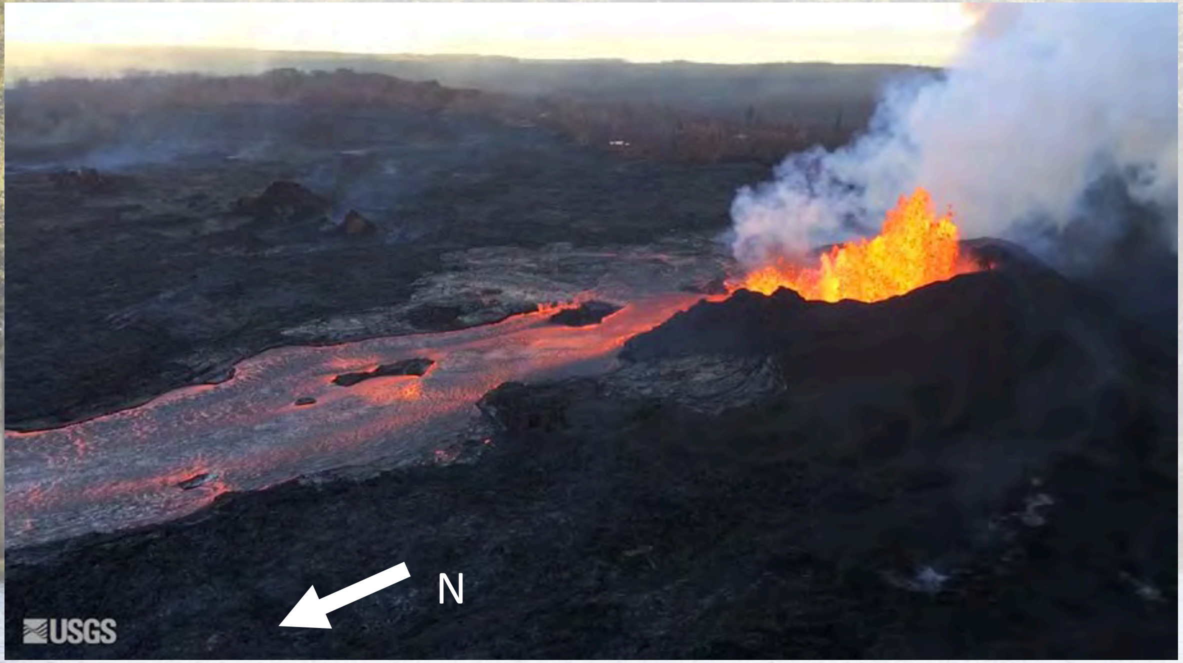


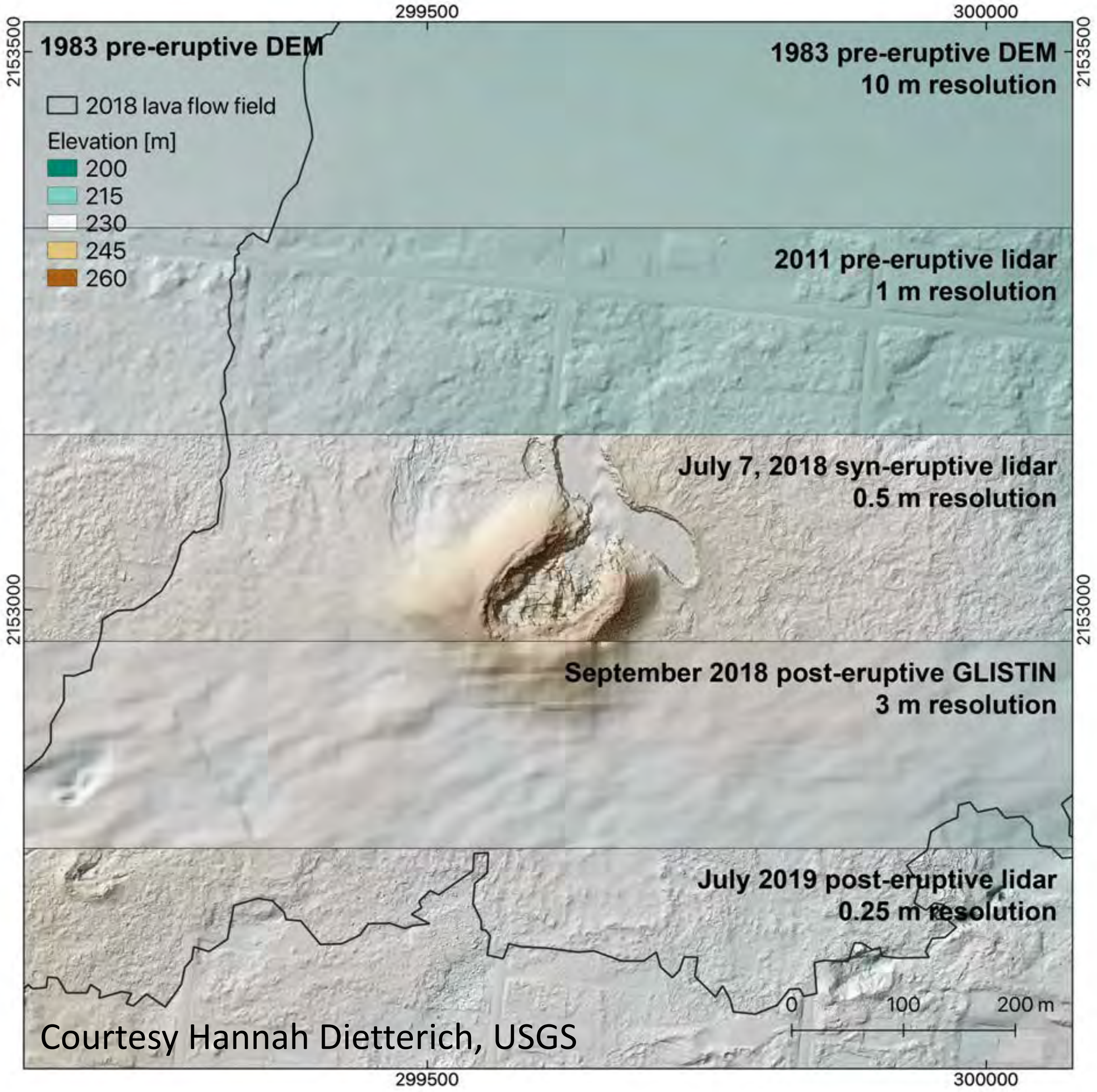


Lundgren et al. (2019)

Time varying topo: Kilauea 2018 eruption

Comparison of different resolution airborne topography data covering Fissure 8 in the Lower East Rift Zone of the 2018 Kilauea eruption

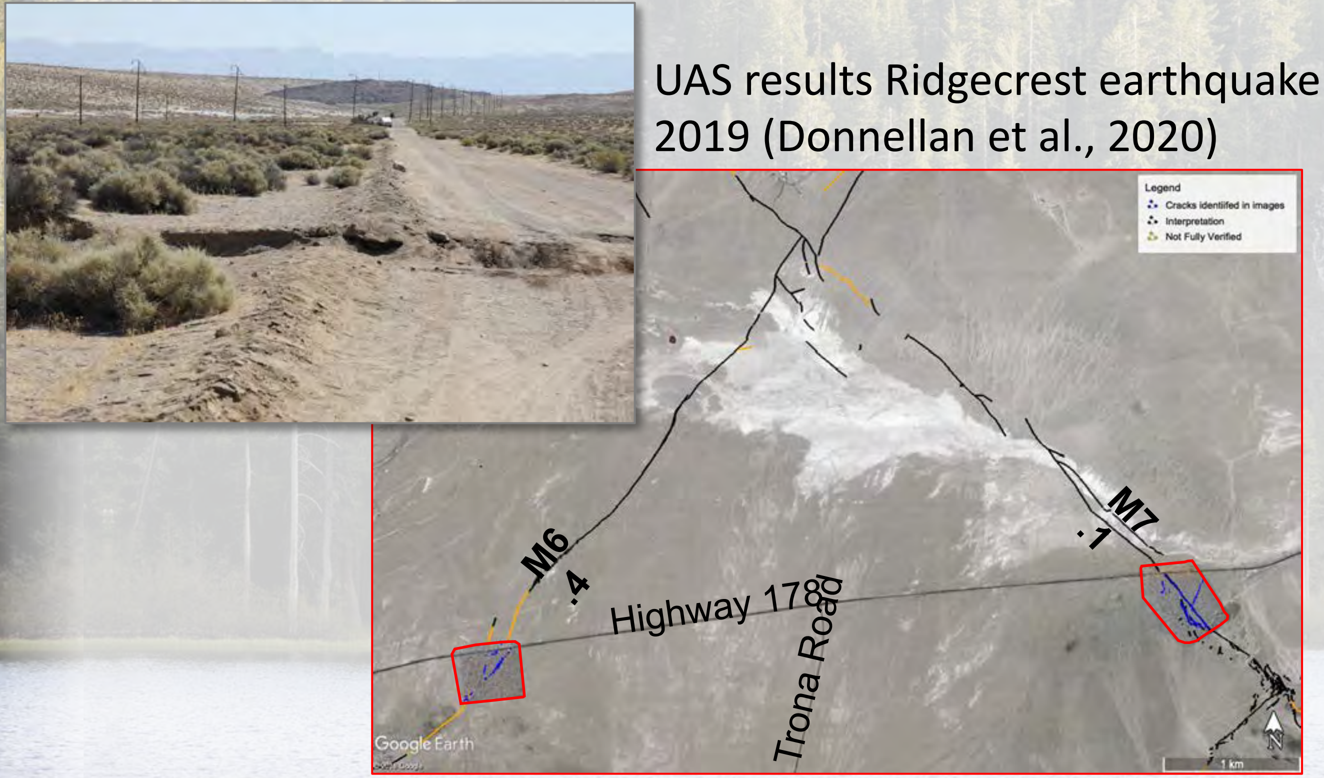




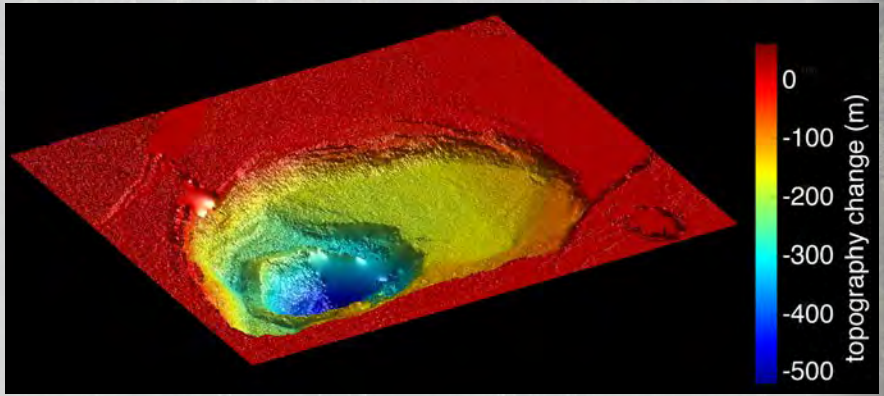
Courtesy Hannah Dietterich, USGS

Physical Parameters

- Surface/bare earth topography
- Bathymetry
- The Solid Earth STV charge is to modify and add to the DS recommendations based on current science and identify gaps



UAS results Ridgecrest earthquake 2019 (Donnellan et al., 2020)



GLISTIN-A Topography change, Kilauea caldera 2018 (Lundgren et al., 2019)

Product Needs

- State of the art:
  - Satellite topography: TanDEM-X (12 m / 1.4 m), LIDAR (too coarse)
  - Airborne:
    - SAR – GLISTIN-A (3 m / ~1-3 m, range dependent)
    - LIDAR – LVIS (20 m /xxx)
    - Photogrammetry – (<1 m / <0.1 m ?)
- Gaps
  - Global coverage at high resolution
  - Repeat intervals to meet science needs (requires short repeat interval or observational agility)

Where are the Gaps?

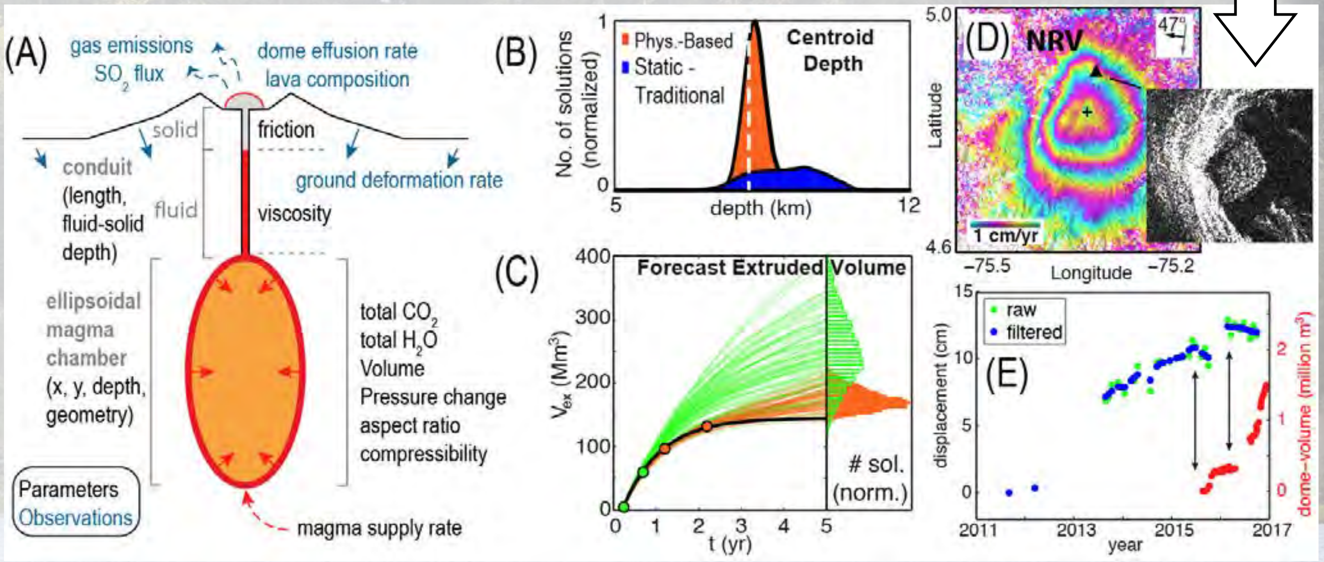
Gap filling

- Ideally product needs are guided by parameter estimation and forecasting needs
- Could be achieved through a combination of OSSEs (below) and technology development
- This is often made difficult by model limitations and smooth fall-off in parameter estimation with degradation in product quality


Nevado del Ruiz volcano
Colombia

Volcano physical dynamic models are constrained by time varying surface deformation and mass flux

Lava dome volume change (topography)



Simulation courtesy Kyle Anderson, USGS

Topographic data and topographic geodesy for solid Earth applications:

Earthquakes, tectonics, landscape change

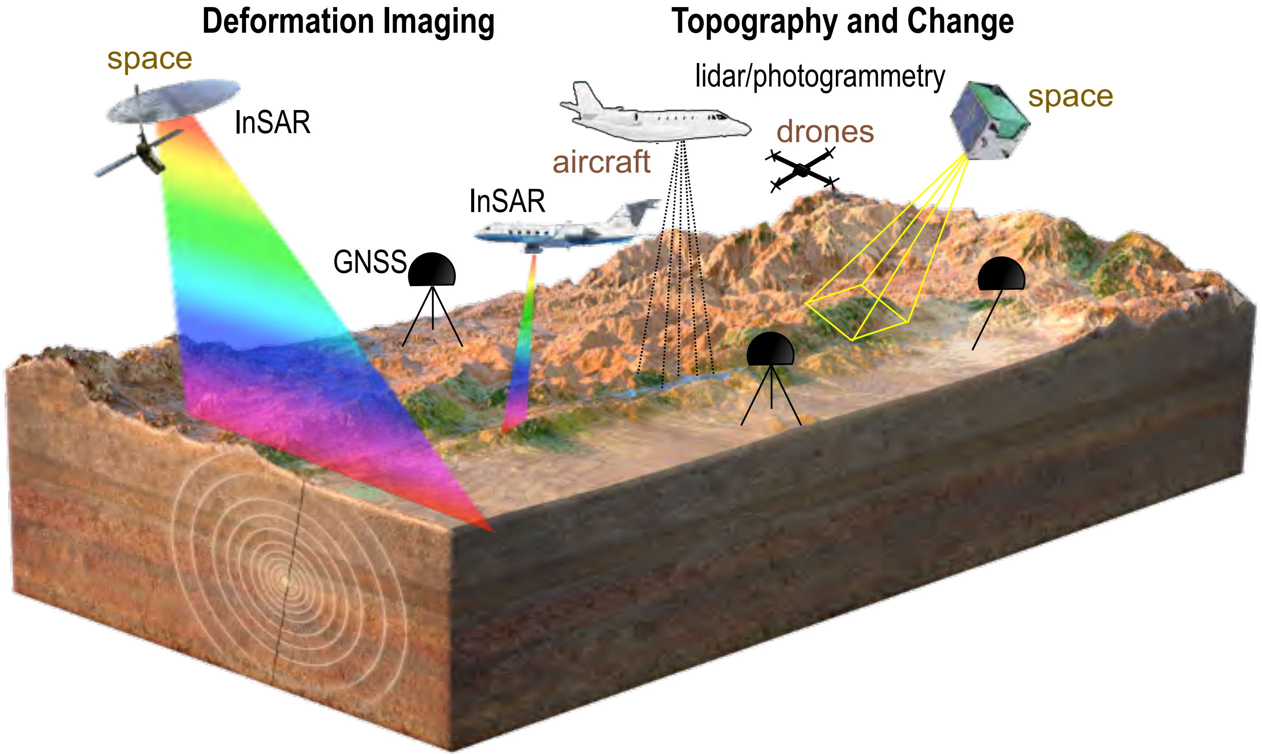
Stephen DeLong

USGS Earthquake Science Center
Moffett Field, CA

U.S. Department of the Interior
U.S. Geological Survey

Science Needs for Earthquake and Related Research

- **High Resolution Topography (HRT) for fault mapping and fault zone research (Earthquake Geology) – Static data**
  - Identify active traces of faults
  - Identify tectonic landforms and structures
  - Identify fault segmentation, linkages among faults
  - Identify sites to investigate earthquake history and fault slip rates
  - Morphologic analyses – scarps, offset features etc.
  - Needed internationally
- **Topographic data for deformation analyses – Repeat data**
  - Coseismic slip
  - Fault Creep
  - Distributed deformation – blind faulting
  - Landslides and rockfall
  - Urban and lifeline infrastructure damage
  - Post-seismic deformation
  - Triggered slip on nearby faults
  - Ground failure and liquefaction
  - Fault zone process, buried slip, evidence for structural, topographic, rheological control on faulting
  - **Pre-event data must be collected**
  - **Repeat data collections at high spatial and temporal resolution**



Measurement	Asset	Coverage	Spatial Resolution	Measurement Resolution	Temporal Sampling
Morphology	Small UAS	< 1 km x 1 km	5–10 cm	decimeter	infrequent
Topography	Lidar	<10 km x 100 km	sub-meter	decimeter	0.5 – 1 year
Surface motion	UAVSAR	15 km x 90 km	7 m	cm differential	0.5 – 1 year
Surface motion	GPS	global	~10 km	1 mm/yr	sub-daily
Surface motion	*NISAR*	*global*	*100 m*	*cm differential*	*12 day*
Morphology	*Air/spaceborne*	*<5 km x 100 km*	*50 cm*	*1 m*	*TBD*

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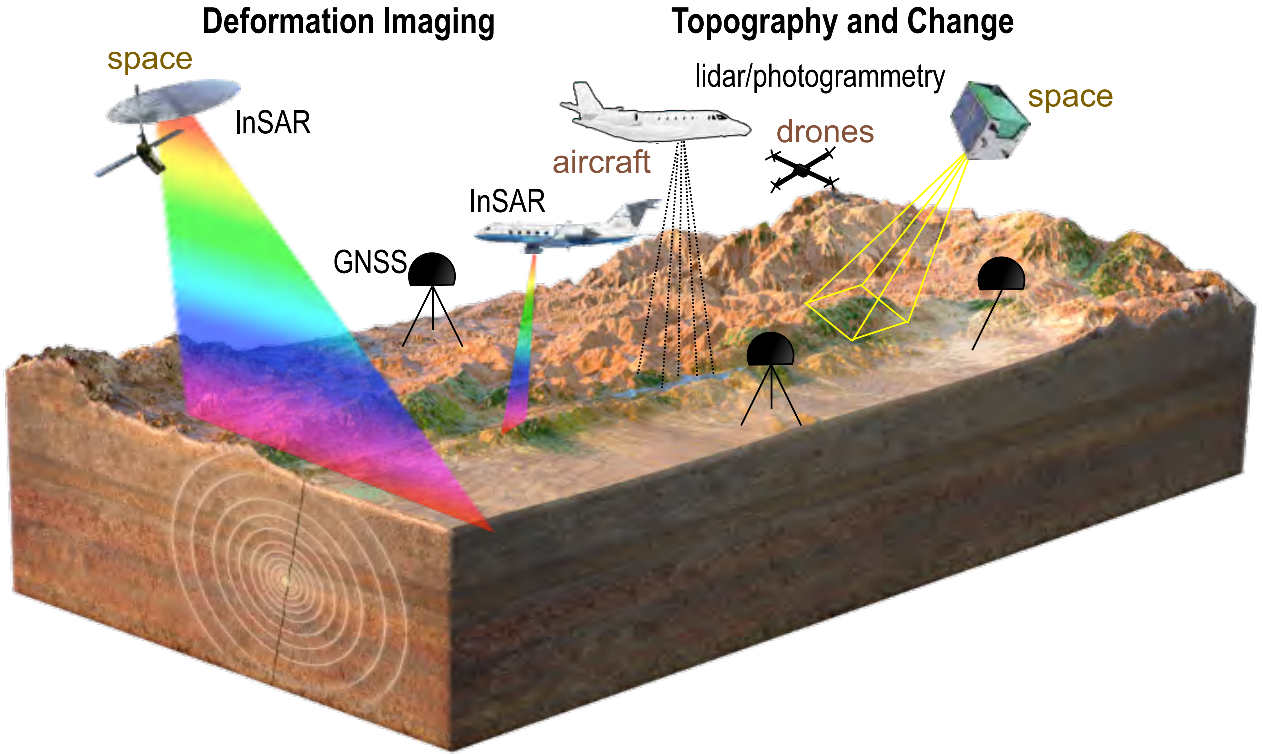
USGS

Science Needs for Earthquake and Related Research

- **High Resolution Topography (HRT) for fault mapping and fault zone research (Earthquake geology)**
  - Meter and sub-meter resolution is the standard for studying fault zones
  - >1 meter data much less useful due to inherent scale of fault zone features
  - Airborne ***lidar*** in vegetated areas
  - SfM and ASP (an other) topographic data from ***optical imagery*** in low-vegetation areas
  - Need internationally – US on its way to full coverage (USGS 3DEP) but international hazard research is hampered by sparse HRT data, especially in vegetated areas
- **Topographic data for deformation analyses (geology and geodesy)**
  - **SAR**
  - Optical data – legacy data can be processed, airborne and spaceborne
  - Lidar – airborne, ground-based, space-based?
  - UAS – lidar, imagery etc.
  - **Pre-event data must be collected**
  - **Repeat data collections at high spatial and temporal resolution**



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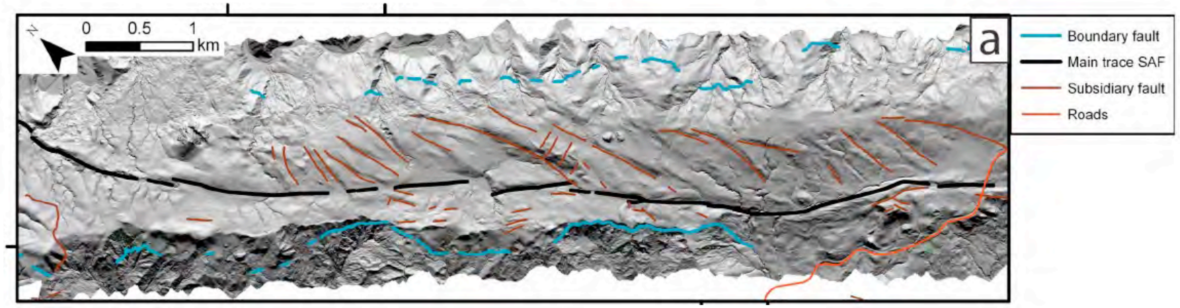
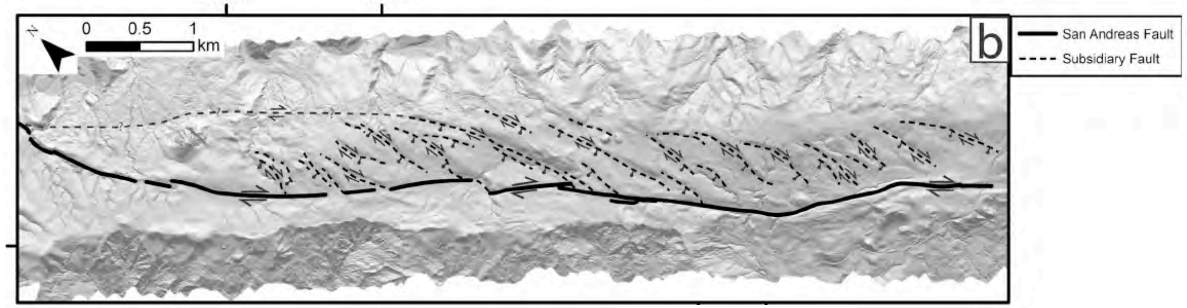
Fault Zone Mapping

Pre-lidar field mapping



Lidar-based mapping



Unpublished data
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“Kinematic” mapping: Windowed ICP on repeat airborne lidar

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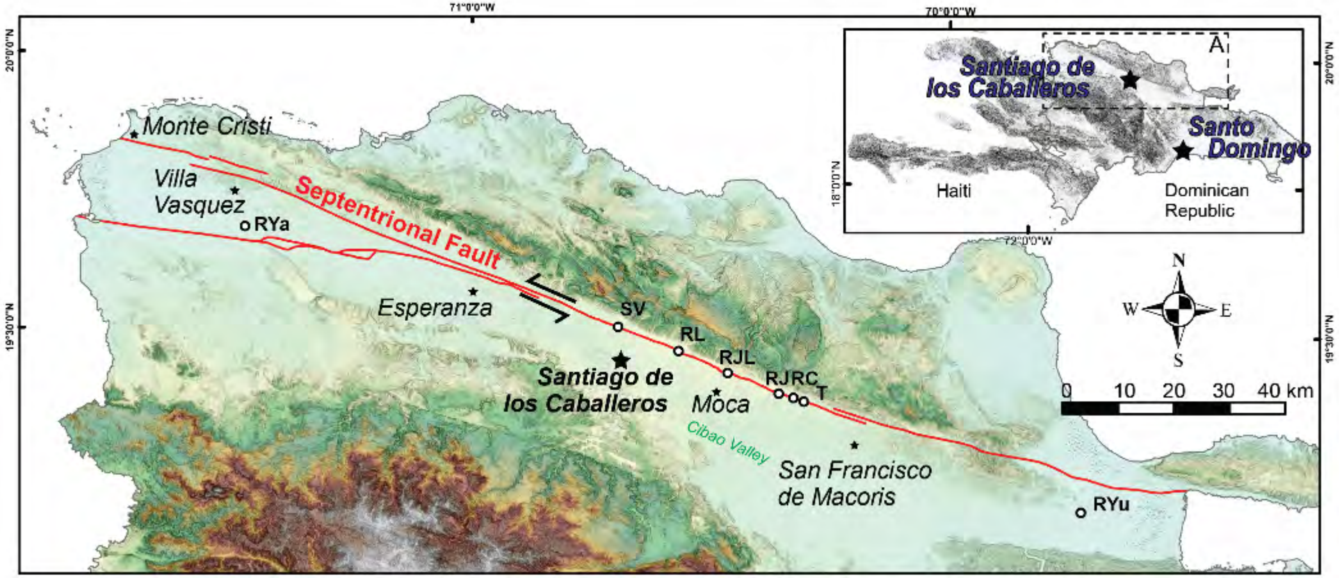
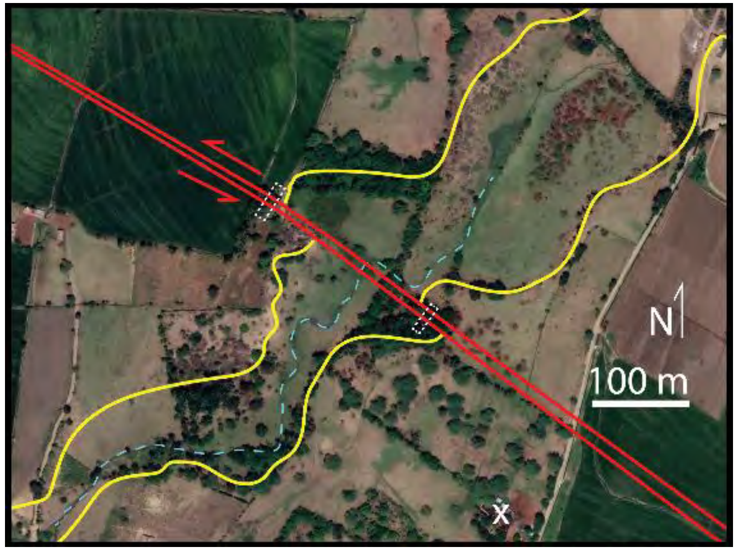
Fault Zone Mapping – International challenges



Dominican Republic has high seismic hazard and no high resolution topography – Optically-derived topography not useful due to vegetation – we use Google Earth for mapping and study site reconnaissance

How do we address need for HRT in at-risk developing nations?



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Recent methodological advances and data needs

- **Optical Image Correlation – can be done with "medium" resolution data and recover sub-pixel change**
- **SAR Interferometry (well-established but pushing to higher sensitivities)**
- **Windowed Iterative Closest Point analyses using topography**
- **Challenges: Detection of fault creep, afterslip, small fault ruptures, and distributed deformation**

2019 Ridgecrest EQ surface faulting

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OpenTopography and K. Hudnut

Recent methodological advances and data needs

- **Optical Image Correlation – can be done with "medium" resolution data and recover sub-pixel change**
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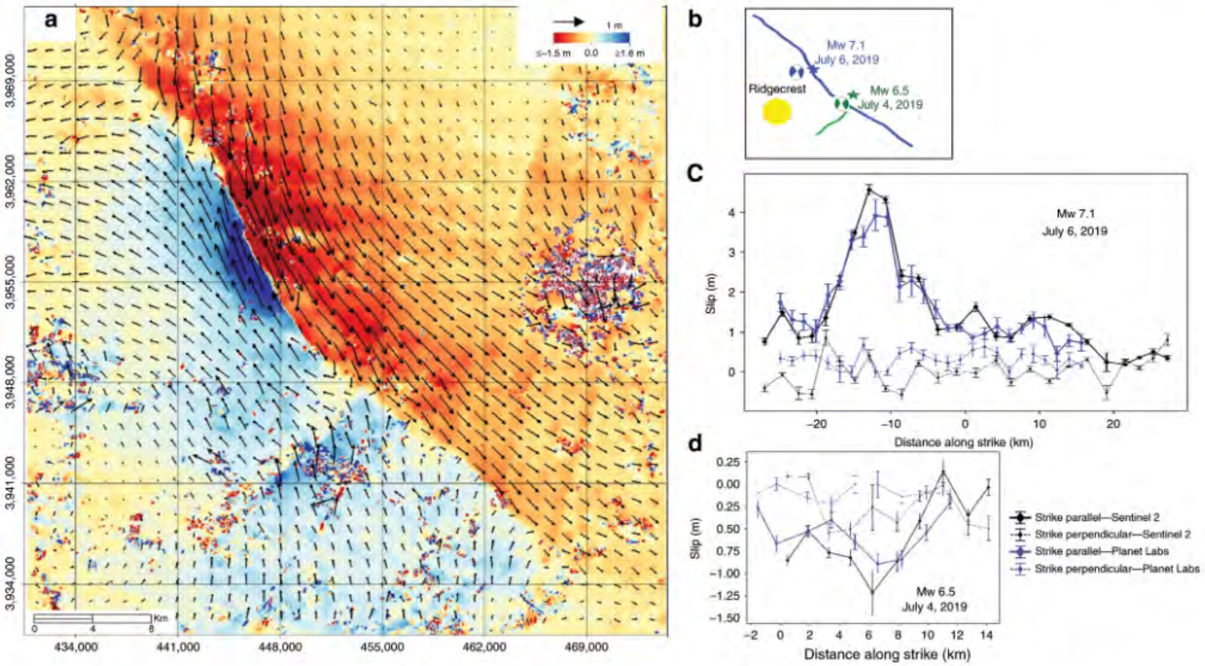
- Detection of fault creep, afterslip, and small fault ruptures and distributed deformation

Fig. 2: Surface deformation due to the 2019 Ridgecrest earthquakes measured from optical image correlation.

From: Cascading and pulse-like ruptures during the 2019 Ridgecrest earthquakes in the Eastern California Shear Zone



a Surface displacement (arrows) and amplitude of NS component (shading) measured from correlation of Sentinel-2 images acquired on June 28 and July 08, 2019. **b** Simplified fault ruptures derived from the Sentinel-1 and Planet Labs data with GCMT focal mechanisms and epicentres of the M_W 7.1 and M_W 6.5 earthquakes from the USGS. **c** Strike-parallel (positive for right-lateral) and strike-perpendicular (positive in extension) component of surface fault slip measured from the Sentinel-1 and Planet Labs image. **d** Same as **c** for the M_W 6.5 earthquake.

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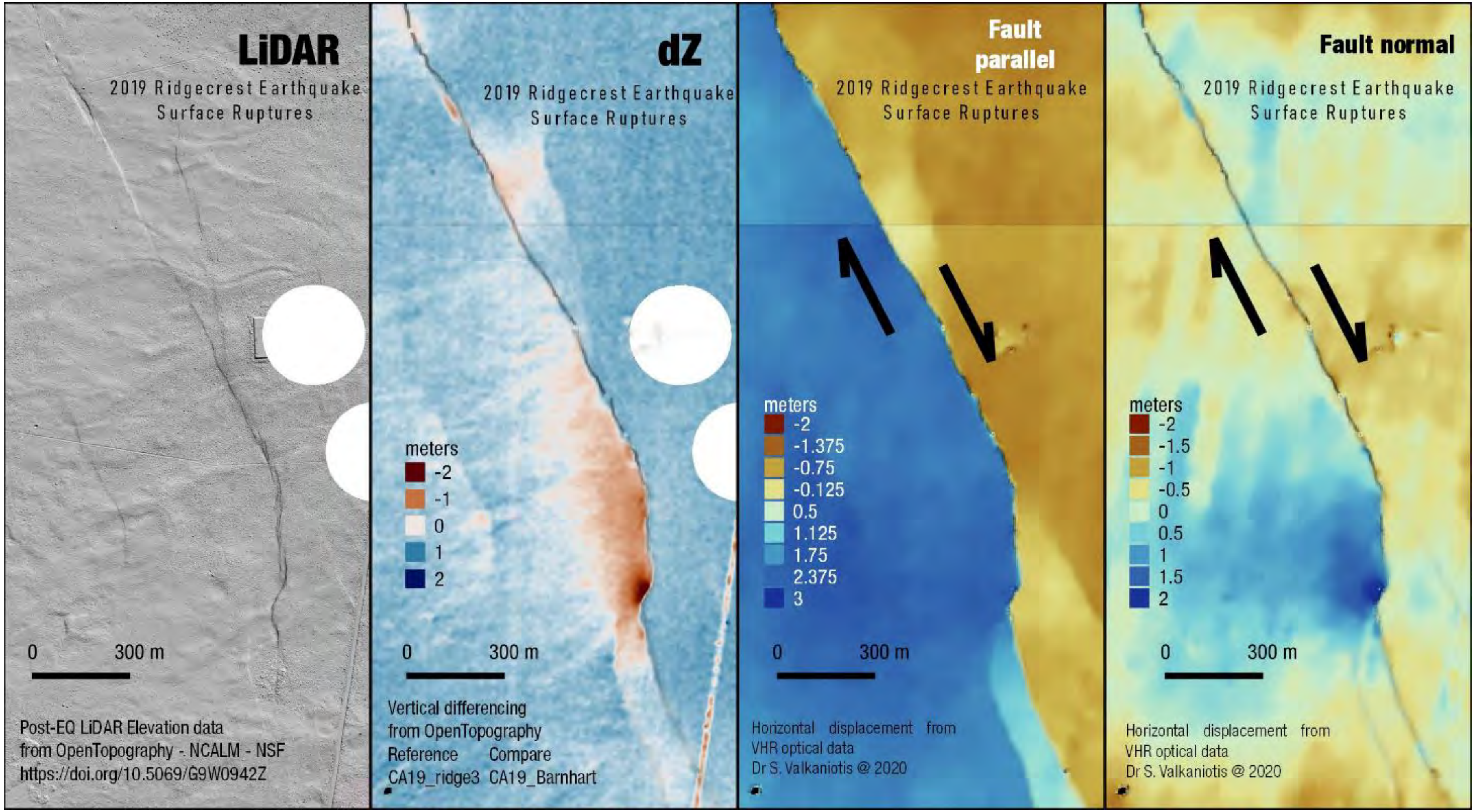
Chen et al 2020

Recent methodological advances and data needs

- **Optical Image Correlation – can be done with "medium" resolution data and recover sub-pixel change**
- **SAR Interferometry (well established but pushing to higher sensitivities)**
- **Windowed Iterative Closest Point analyses using topography**
- **Detection of fault creep, afterslip, and small fault ruptures and distributed deformation**



LiDAR

2019 Ridgecrest Earthquake Surface Ruptures

Post-EQ LiDAR Elevation data from OpenTopography - NCALM - NSF https://doi.org/10.5069/G9W0942Z

dZ

2019 Ridgecrest Earthquake Surface Ruptures

Vertical differencing from OpenTopography
Reference CA19_ridge3 Compare CA19_Barnhart

Fault parallel

2019 Ridgecrest Earthquake Surface Ruptures

Horizontal displacement from VHR optical data Dr S. Valkaniotis @ 2020

Fault normal

2019 Ridgecrest Earthquake Surface Ruptures

Horizontal displacement from VHR optical data Dr S. Valkaniotis @ 2020

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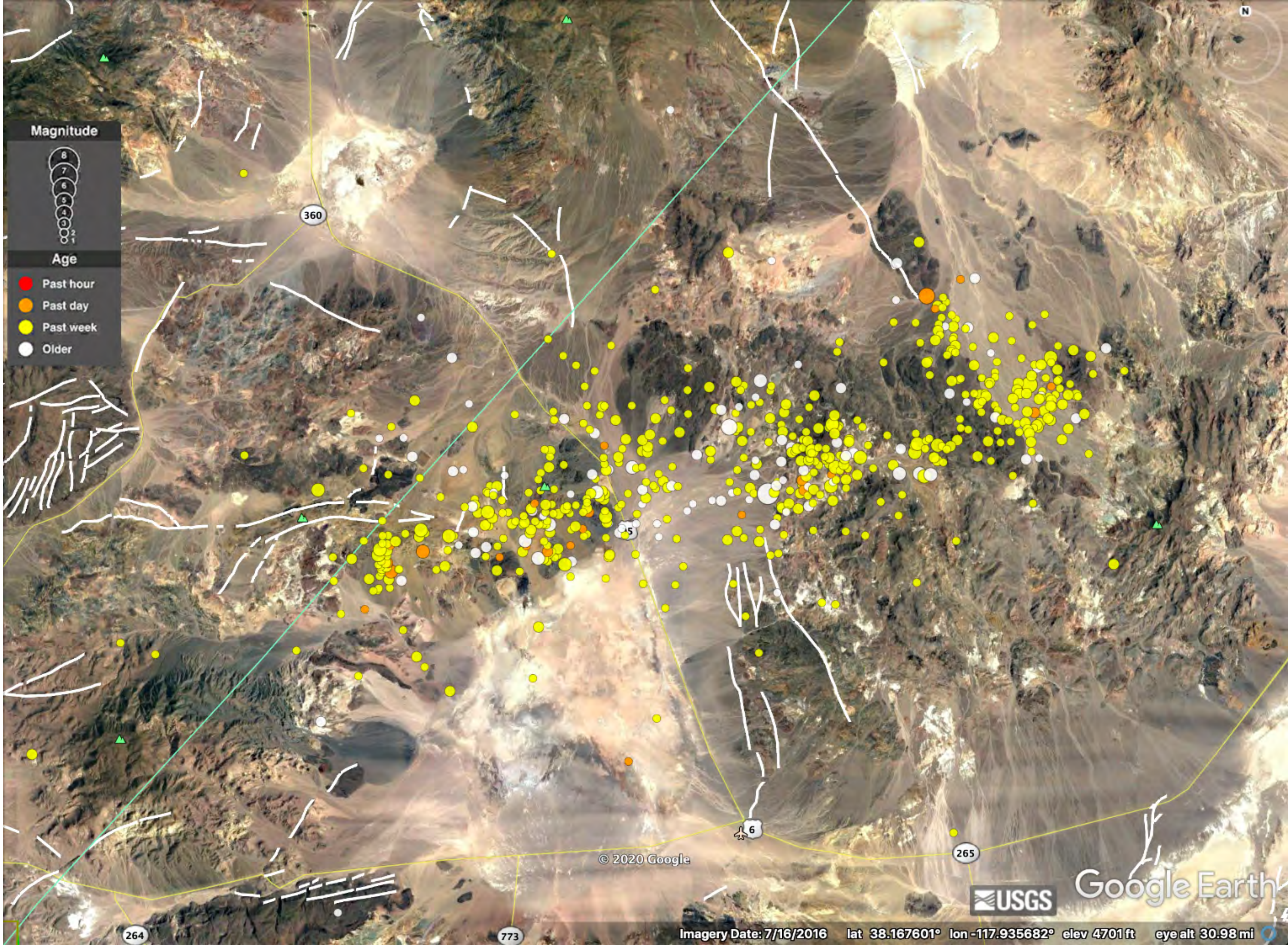
S Valkaniotis via twitter

2020 Monte Cristo Range M6.5 EQ in western Nevada – example of level of detection issues in EQ response in frequent moderate earthquakes.

No pre-event lidar



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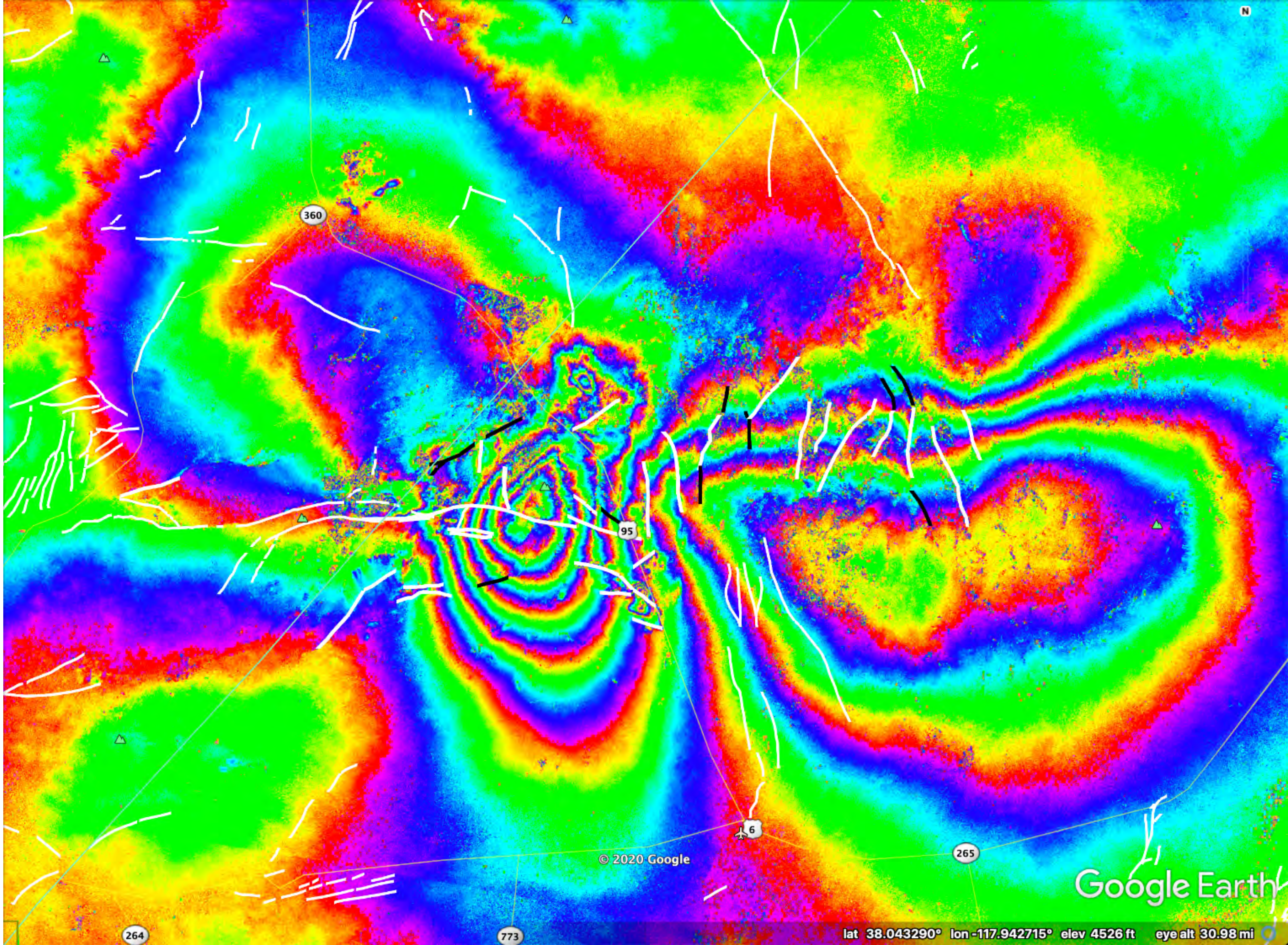
Discontinuities mapped in Descending Sentinel-1 InSAR products were crucial in guiding the field teams to surface faulting, which was minor and distributed in this earthquake and thus difficult to find.



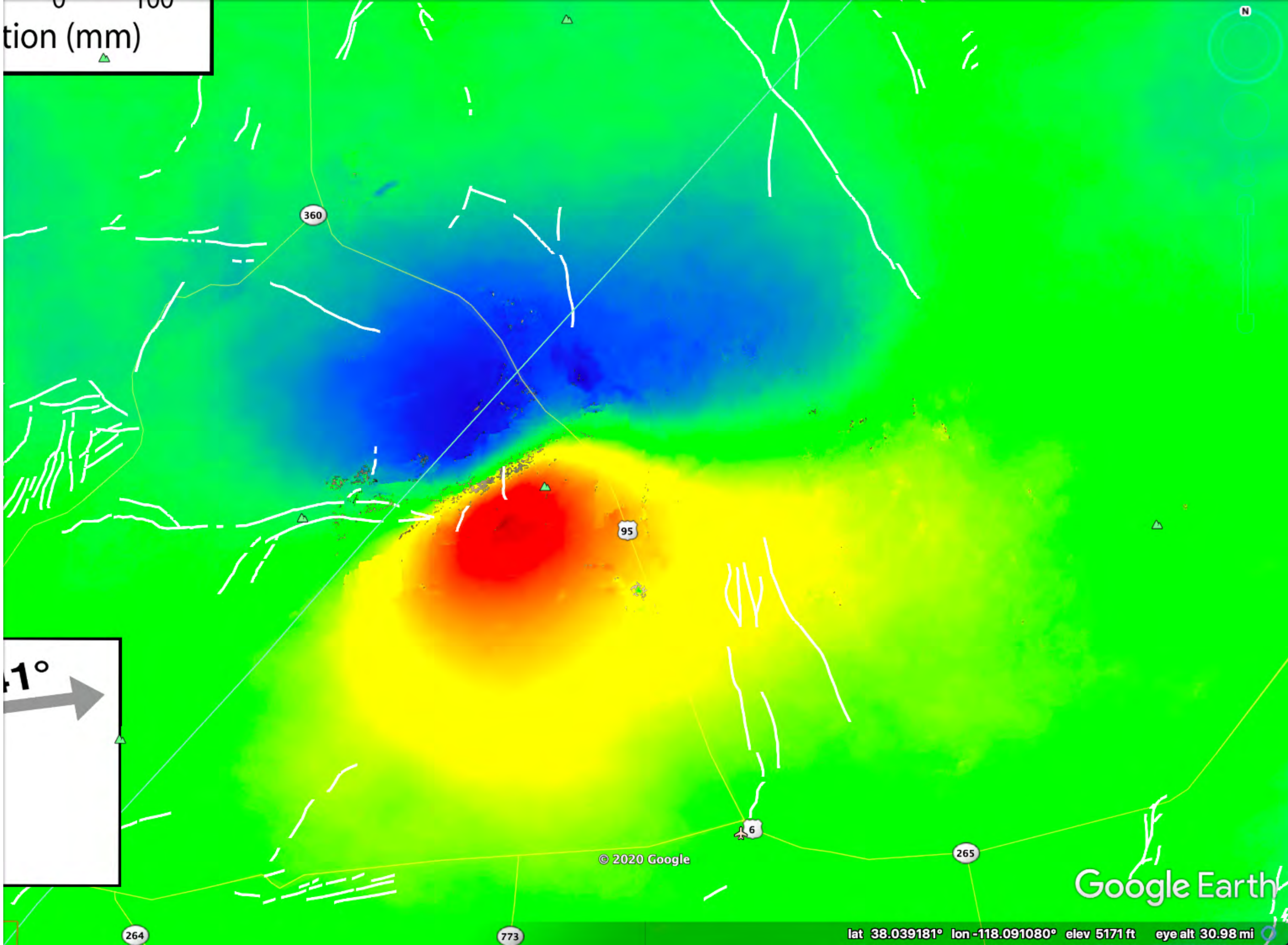
Minor surface faulting found in initial SAR-guided field investigations

One of numerous right-stepping en echelon fractures that could possibly be reconstructed for offset vector; 1-3 cm opening, hint of left-lateral slip

Monte Cristo Range
M6.5 Earthquake
Prelim. Field Report

USGS

Line-of-Sight (LOS) InSAR displacements (C. Wicks) reveal steps *parallel to* the axis of the strongest displacement gradient, suggesting structures sympathetic with the main seismogenic fault



Field-checking these steps led field geologists to the largest left-oblique surface ruptures seen throughout the area (NE-striking, parallel to the County Line)

Unpublished material removed

Main fault (west)

S. Dee of Nevada Bureau of Mines and Geology traced the continuation of the main rupture westward and found increasing offset magnitudes

photo: Seth Dee, UNR

Monte Cristo Range
M6.5 Earthquake
Prelim. Field Report

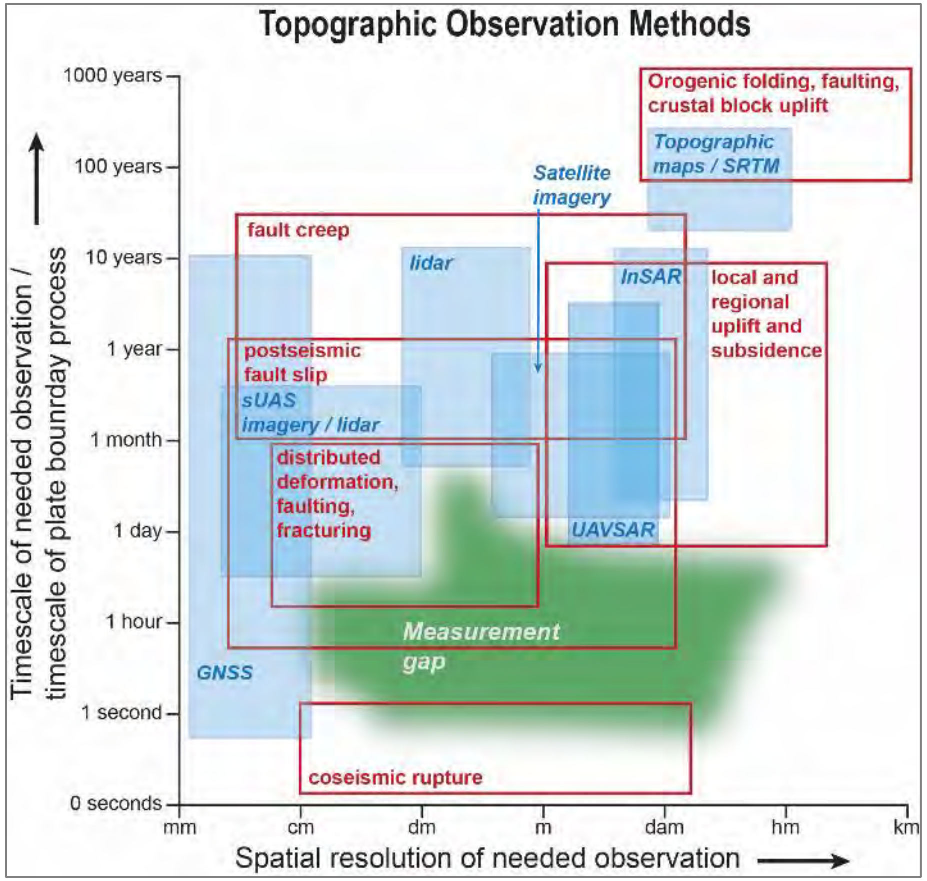
USGS

Ultra high resolution data from sUAS

Science Needs for Earthquake and Related Research

- **Long term objectives - measurement needs:**
  - 1 meter scale **global** topographic data
  - In vegetated areas: lidar HRT
  - In vegetation-free areas: optical or laser HRT
  - Rapid response products following earthquakes, tsunami, floods, wildfire, volcanic activity, landslides, land use changes
  - SAR, optical imagery, and laser scanning topographic data are all very useful

- **Things not discussed…**
  - Ocean bathymetry!
  - Emergent methods and algorithmic developments – AI, ML, etc. on big data that may increase usefulness of existing and/or lower resolution data
  - Increased use of existing data – geologists not always aware of data usability and availability
  - Data management challenges, regional-scale landscape change, interrogating data to understand processes



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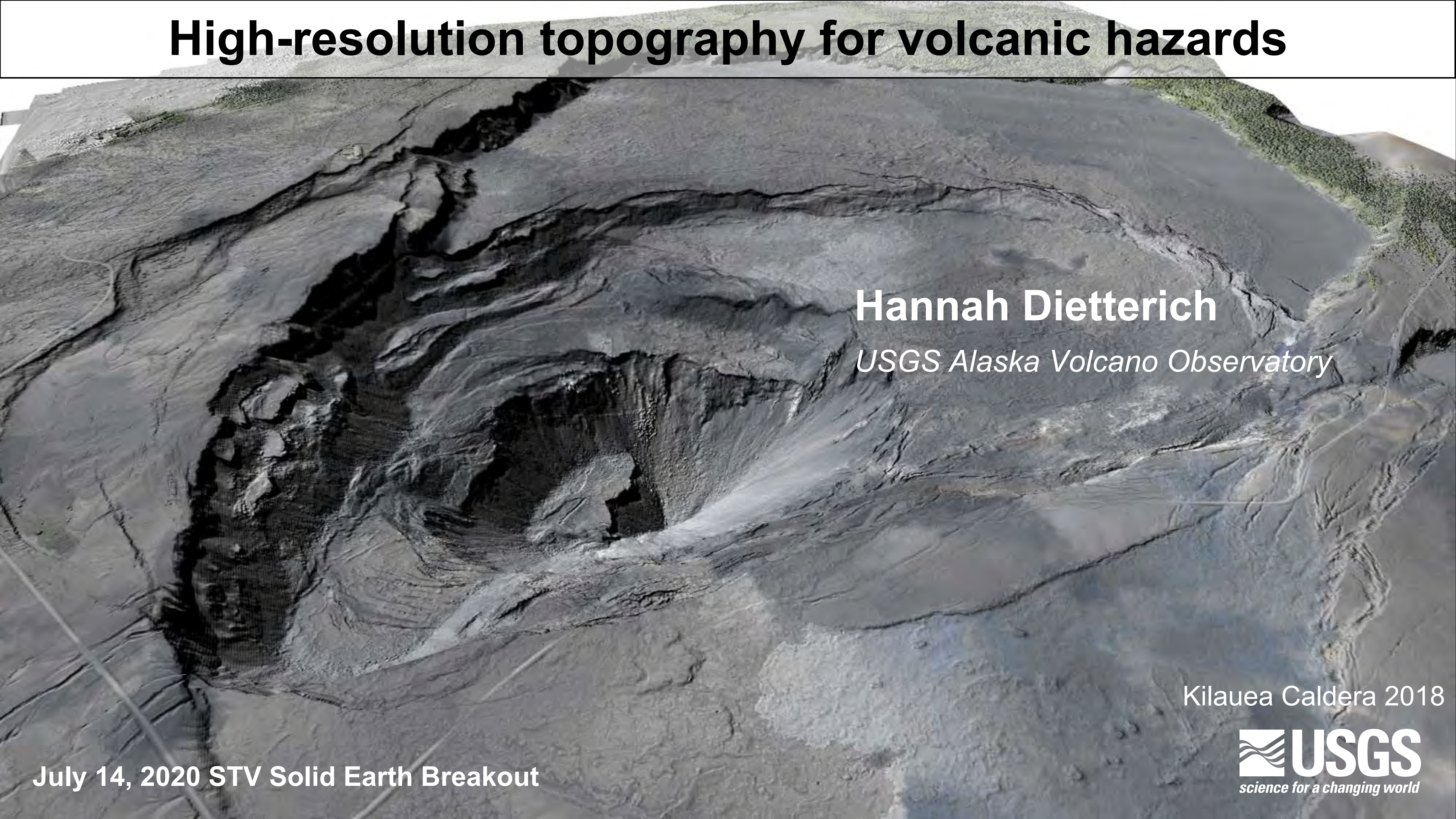
High-resolution topography for volcanic hazards



Hannah Dietterich

USGS Alaska Volcano Observatory

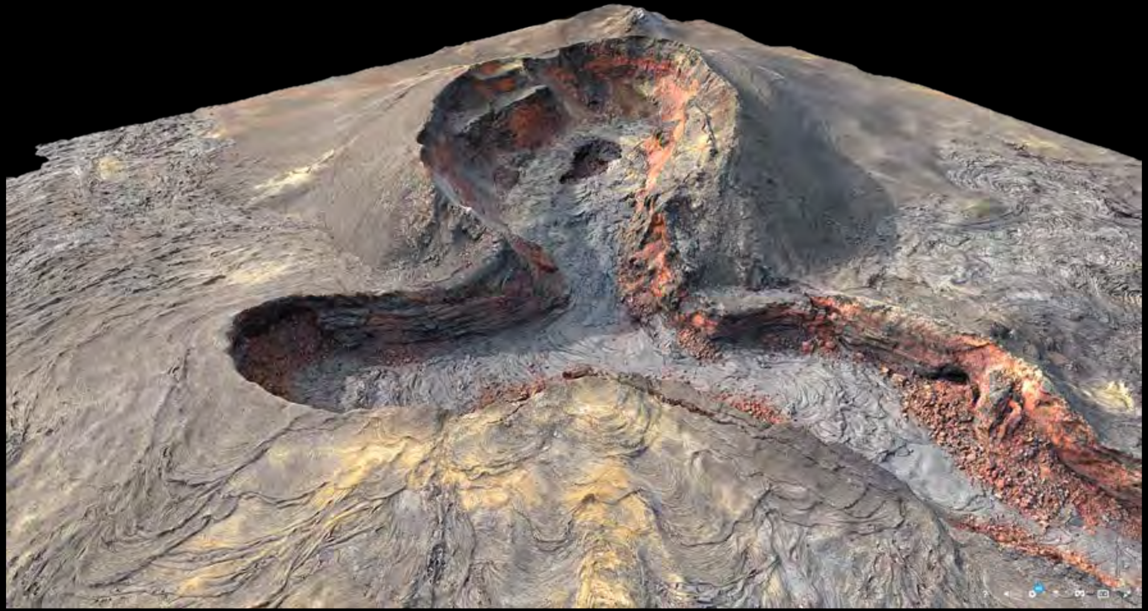
Kilauea Caldera 2018

USGS
science for a changing world

July 14, 2020 STV Solid Earth Breakout

Key questions for hazard assessment and scientific inquiry

- Where, what, and when has a volcano erupted in the past?
- How do edifice and deposit morphology reflect eruptive processes and dynamics?
- How does change in topography reflect volcanic unrest and eruptive processes?
- What areas are at risk from volcanic hazards?

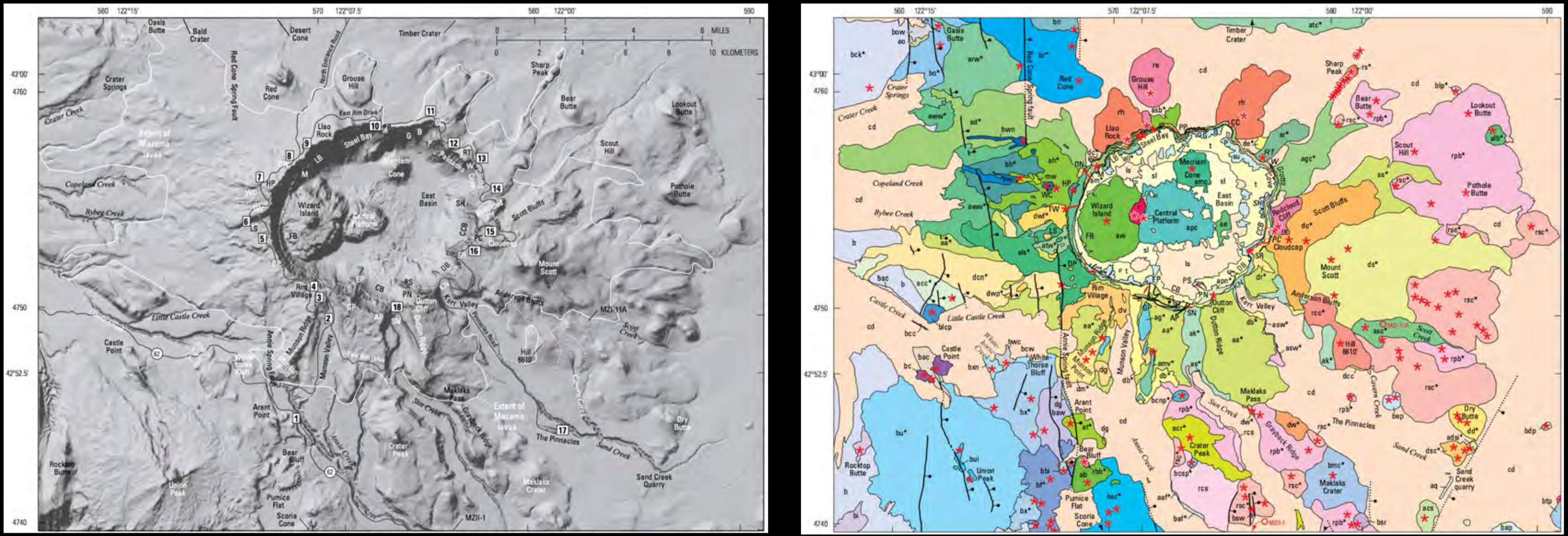


Kilauea 2018 lava flow – fissure 8

Hawaii Aerial Visions

- ➢ **Volcano hazards and research requires topographic data at high spatial and temporal resolution**

Topographic data for geologic studies



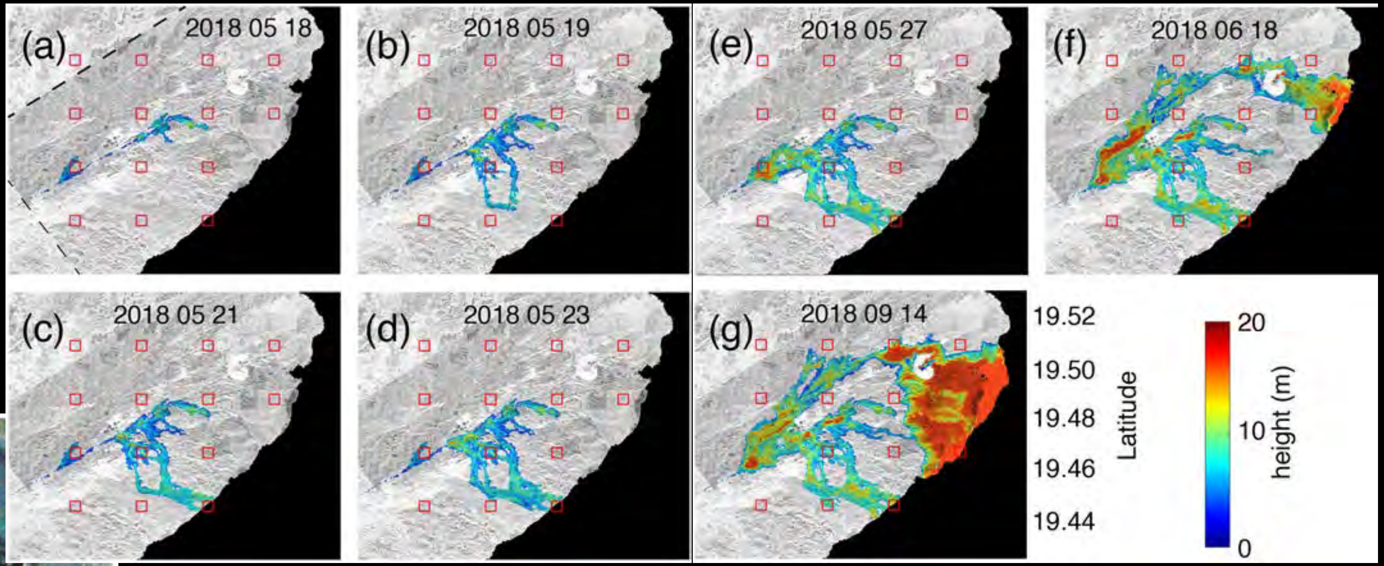
Crater Lake terrain and geologic map

Bacon and Wright 2017

- Characterizing past eruptions, including their locations, volumes, and eruptive styles

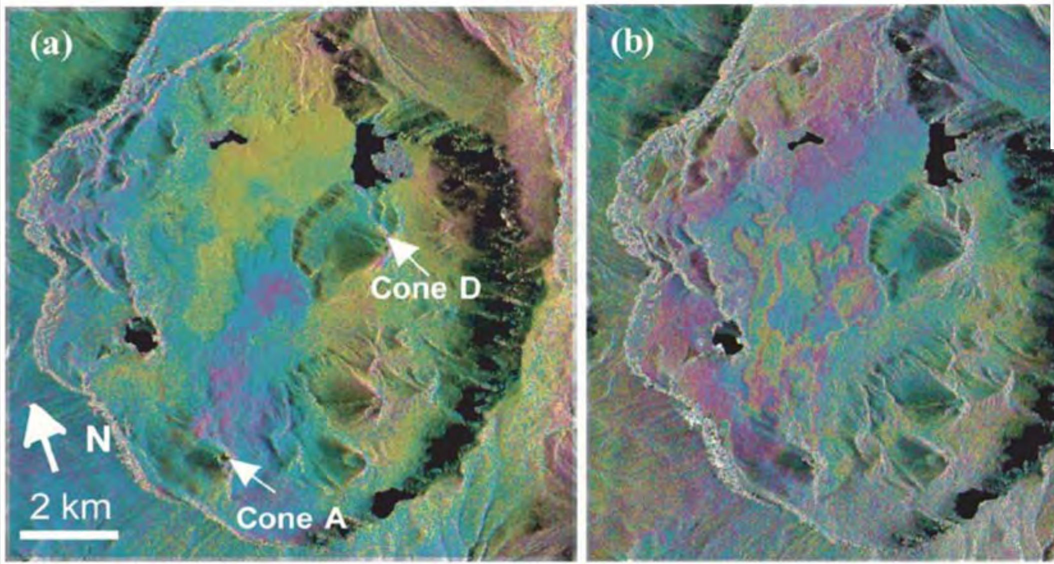
Topographic change for volcano monitoring

- Large-scale volcano deformation and deposition/erosion may be measured by topographic change
- Smaller (mm-cm) scale deformation from InSAR utilizes terrain data



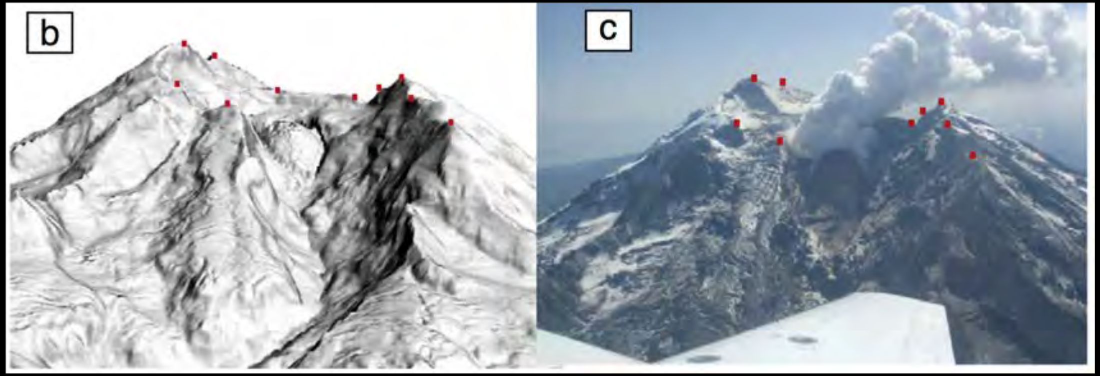
Kīlauea 2018 lava flow

Lundgren et al. 2019



Okmok 1997 lava flow

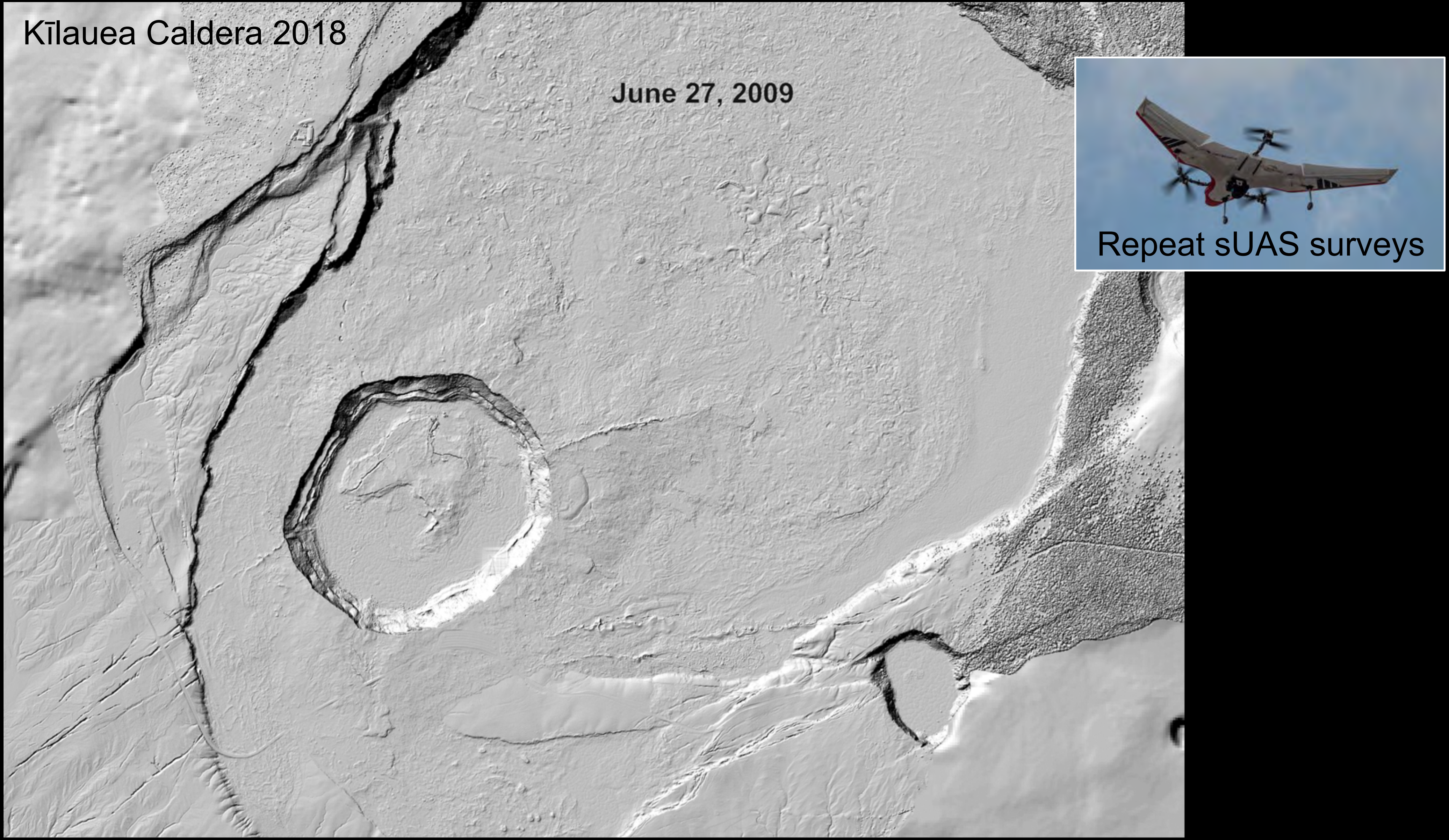
Lu et al. 2003



Redoubt 2009 lava dome growth

Diefenbach et al. 2013

Topographic change for volcano monitoring

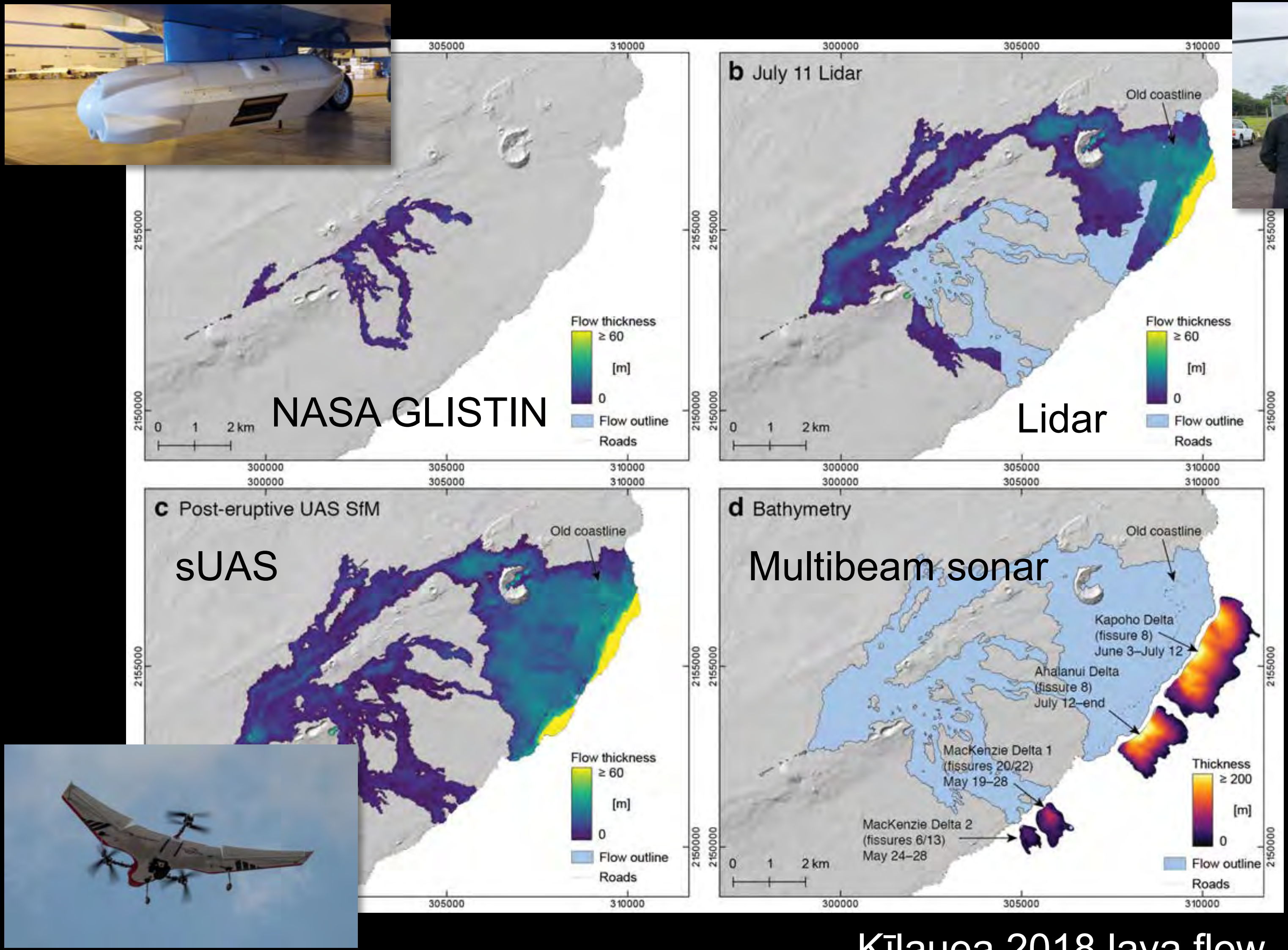


Kīlauea Caldera 2018

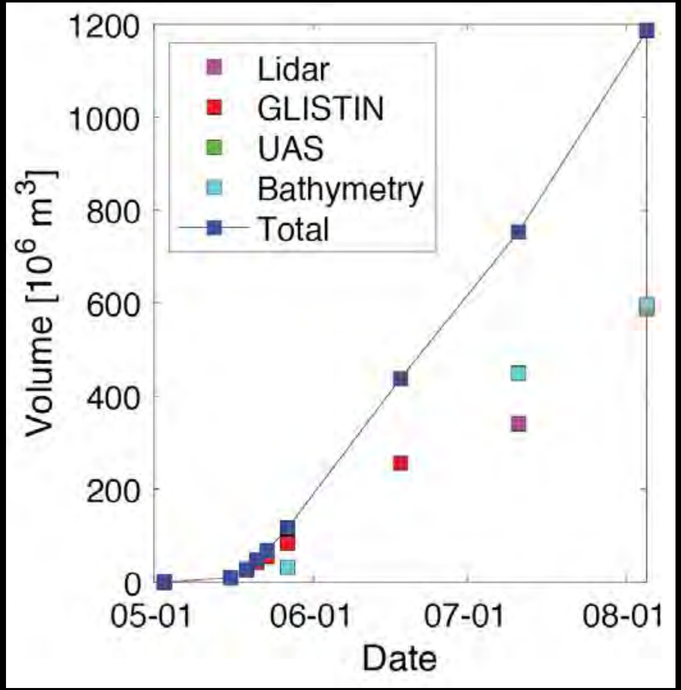
June 27, 2009

Repeat sUAS surveys

Topographic change for volcano monitoring



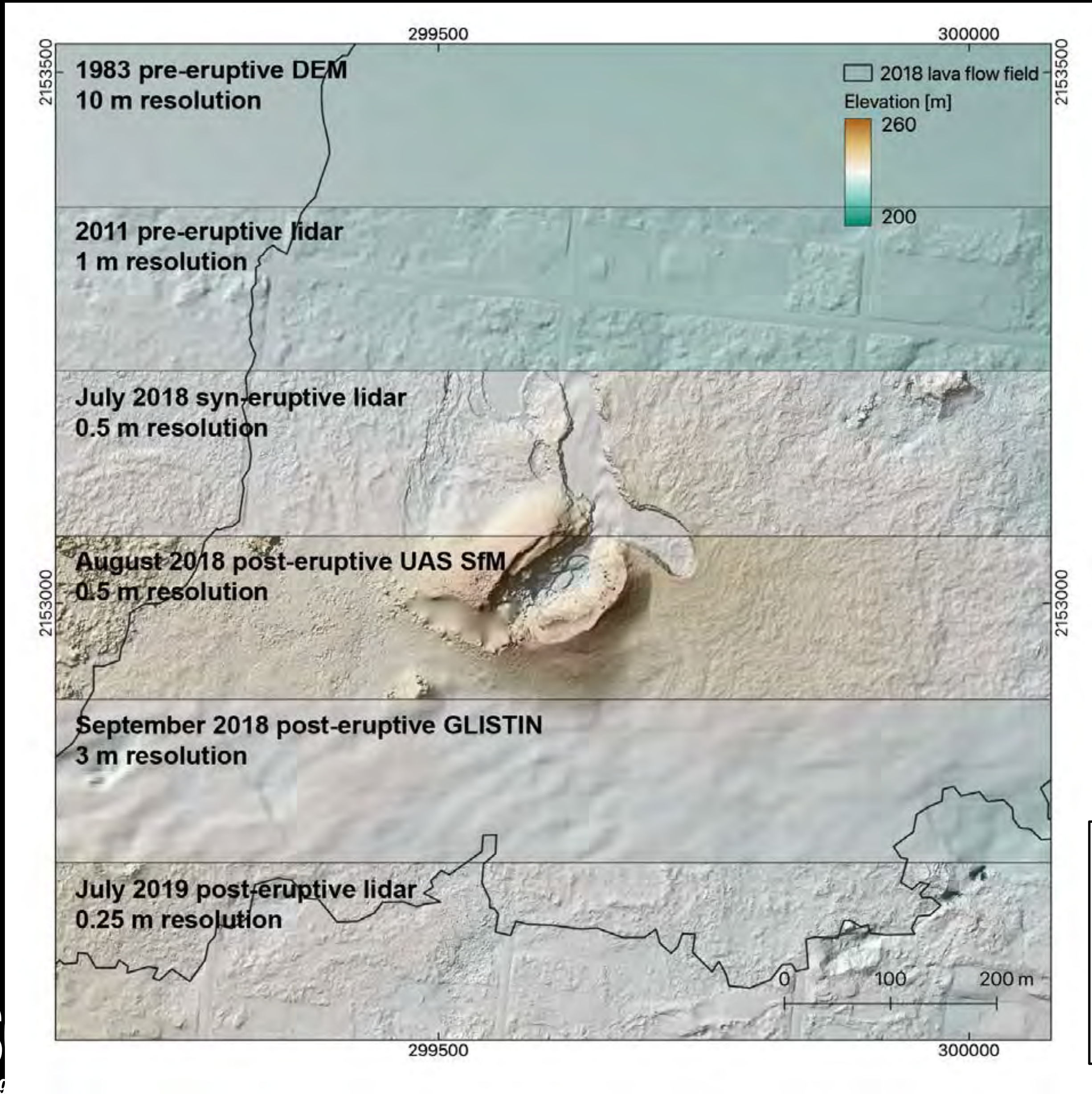
Lava effusion rate and volume



Kīlauea 2018 lava flow

Dietterich et al. in prep.

Topographic change for volcano monitoring



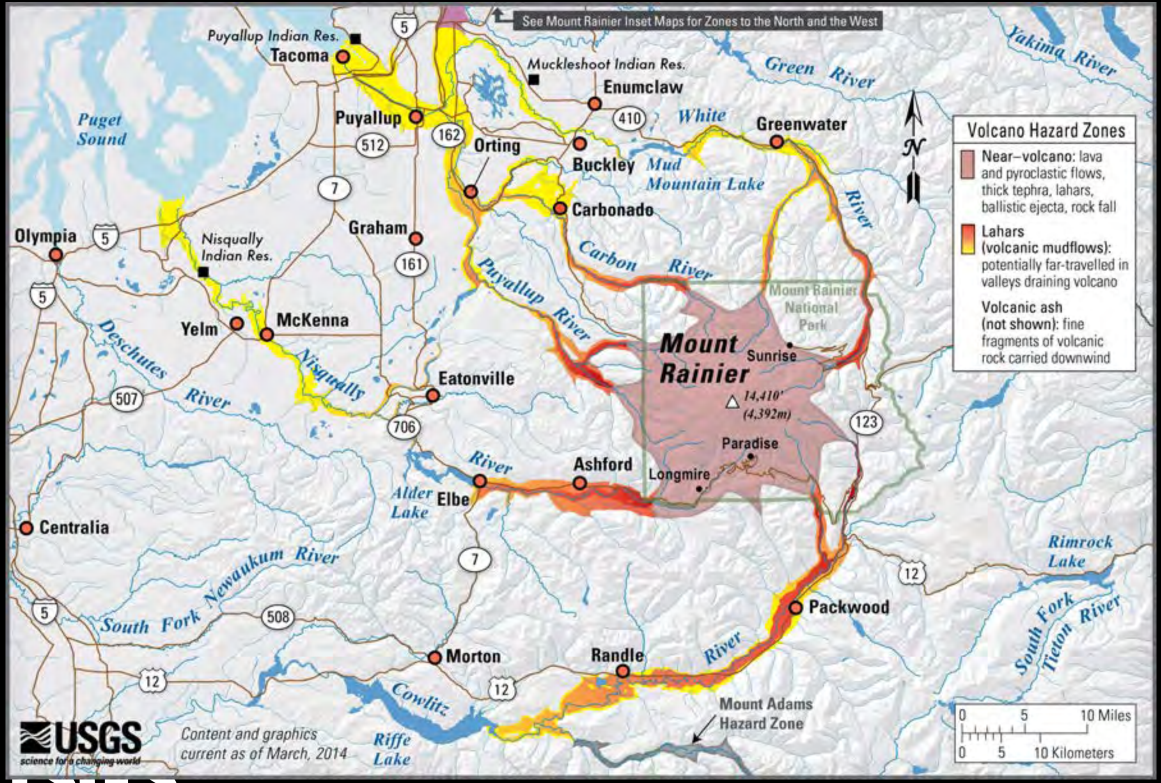
Current state-of-the-art:

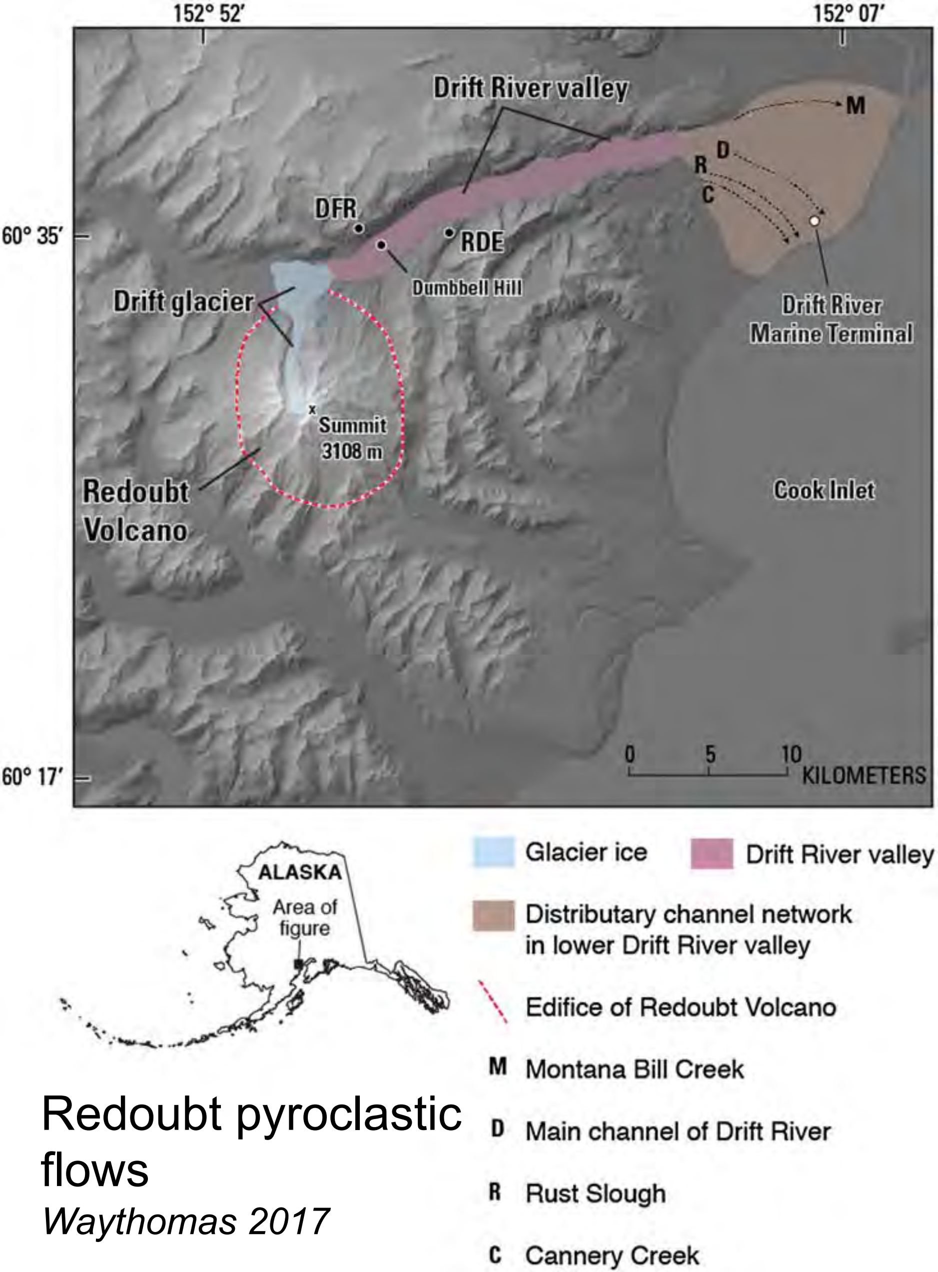
- Satellite and airborne SAR
  3–5 m, edifice-scale
- Satellite photogrammetry
  ~1 m, edifice-scale
- Airborne lidar
  0.25–1 m, bare-earth, limited extent
- sUAS structure from motion
  0.1–1 m, 45 min return, very limited extent

Volcanic hazard assessment

- Volcanic flows are sensitive to topography and require accurate and high-resolution data

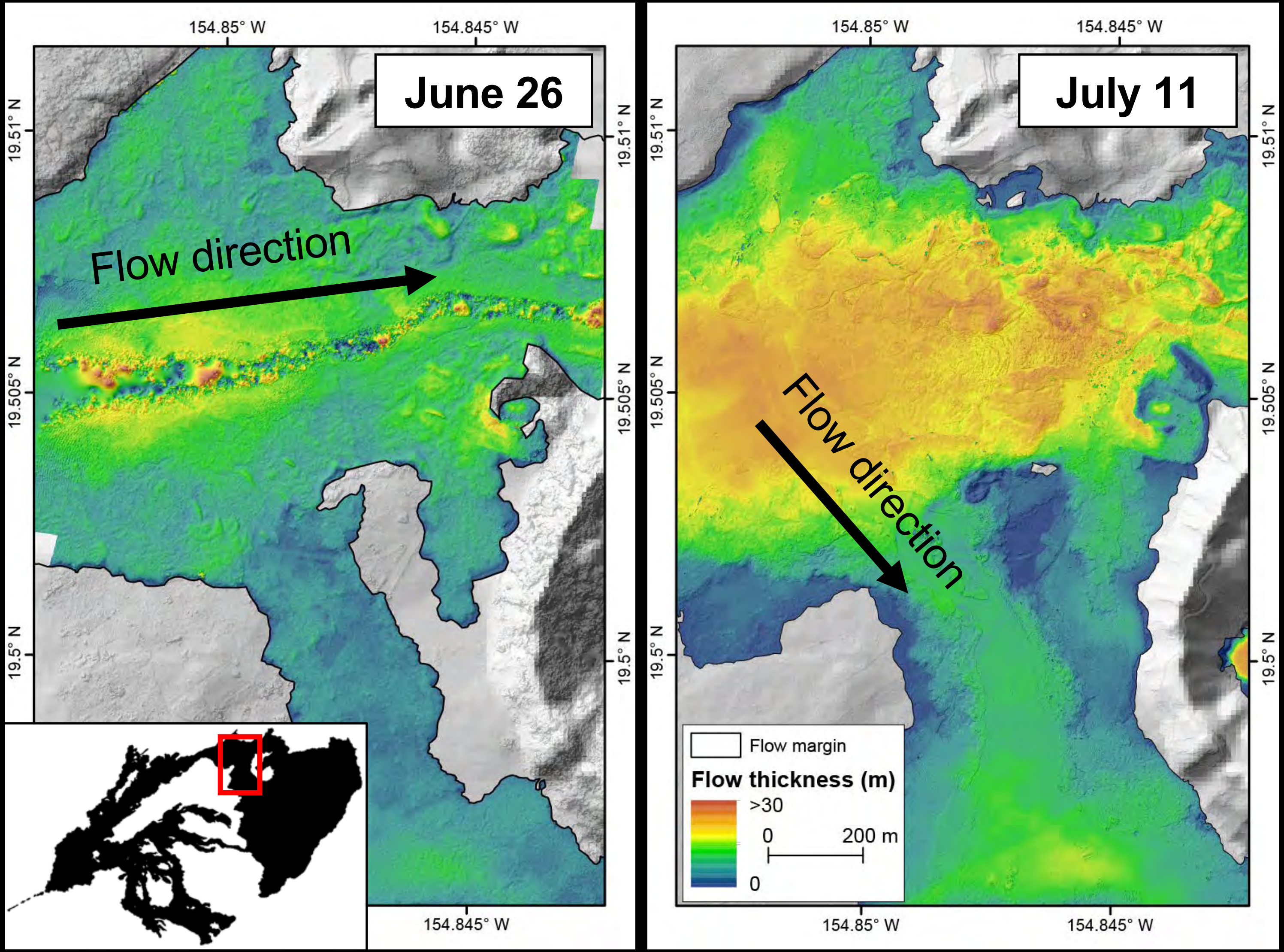
Rainier lahar hazard map
USGS CVO, 2014



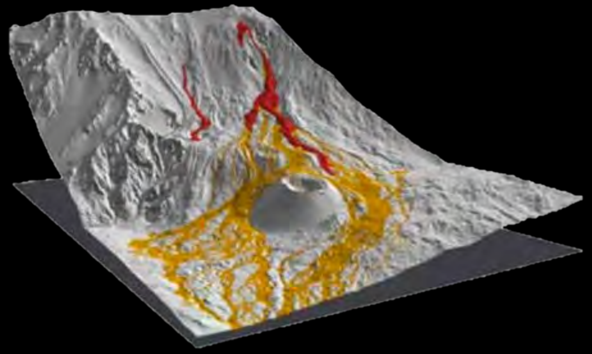


Redoubt pyroclastic flows
Waythomas 2017

Volcanic hazard assessment



- Eruptions may also evolve through time and require updated topography for accurate assessments

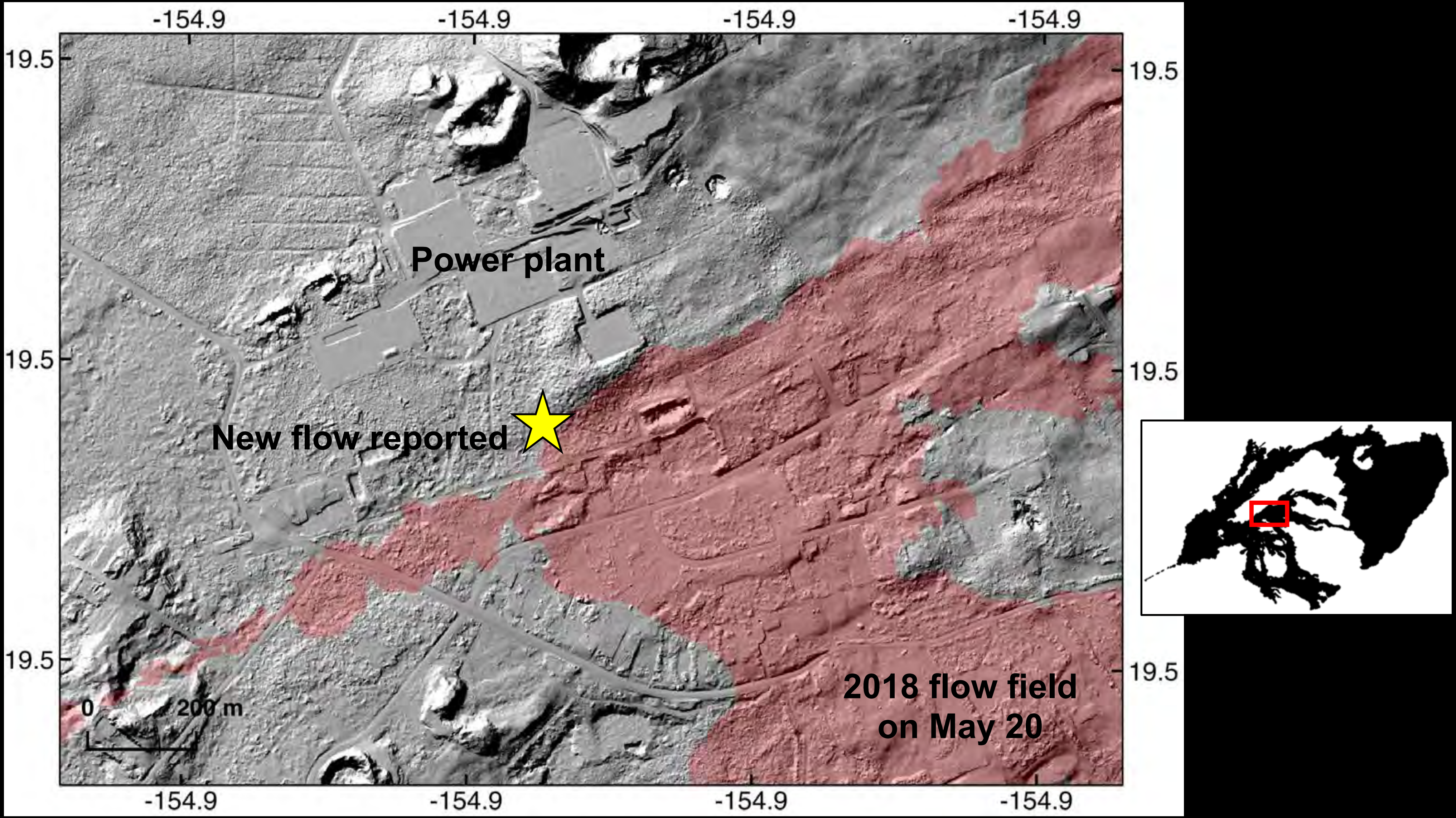


Kīlauea 2018 lava breakout event

Lava flow forecasting

As flows are emplaced, updated topography is needed!

Pre-eruptive lidar

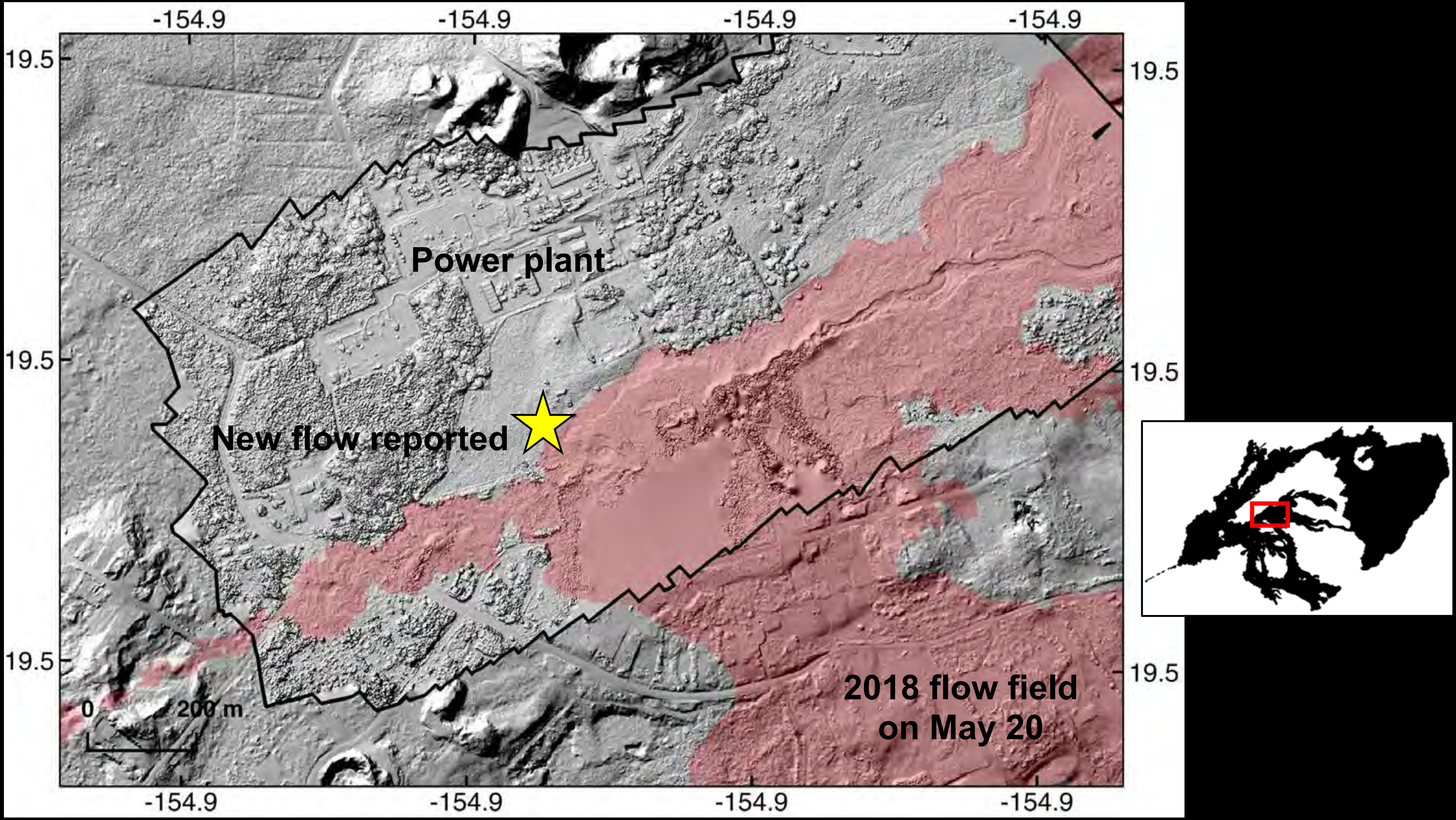


USGS
science for a changing world

Lava flow forecasting

As flows are emplaced, updated topography is needed!

Pre-eruptive lidar + 05-21-2018 UAS DSM

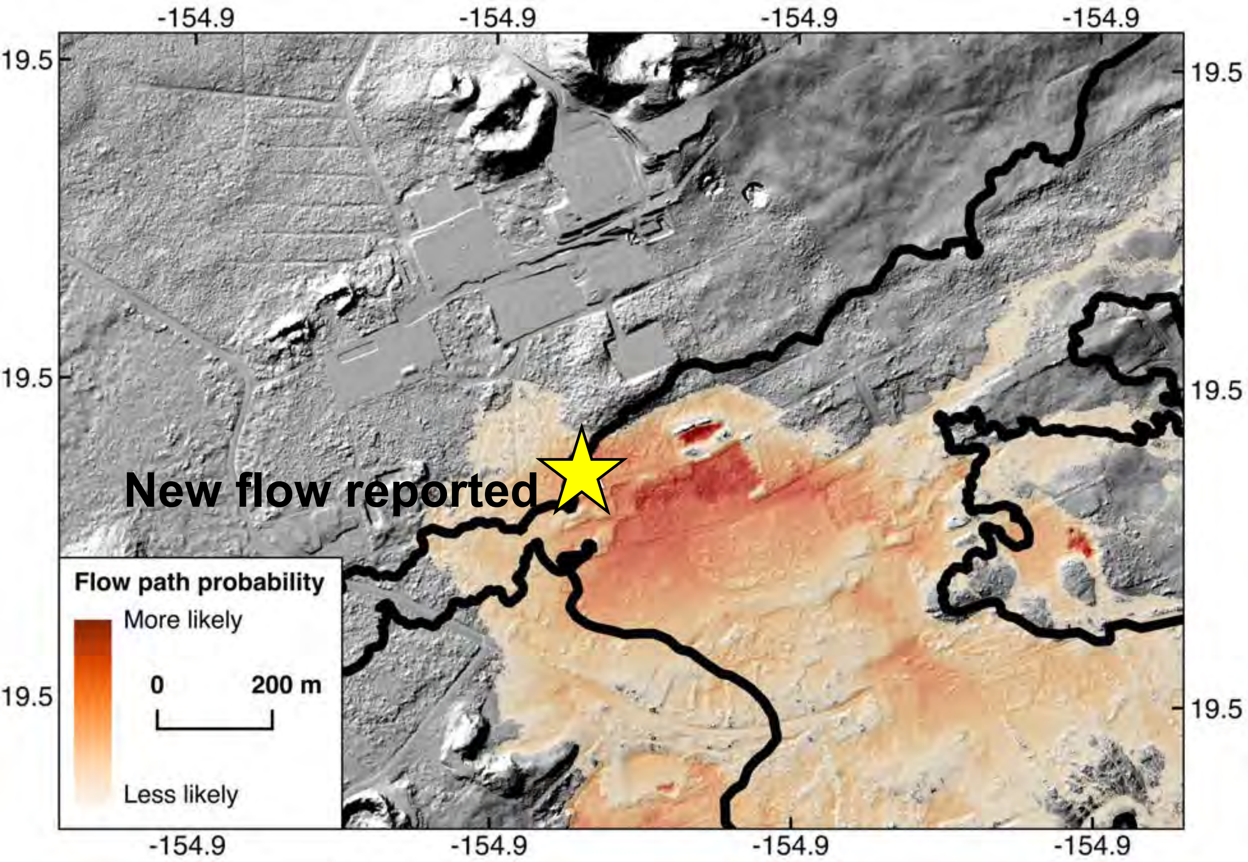


2011 lidar

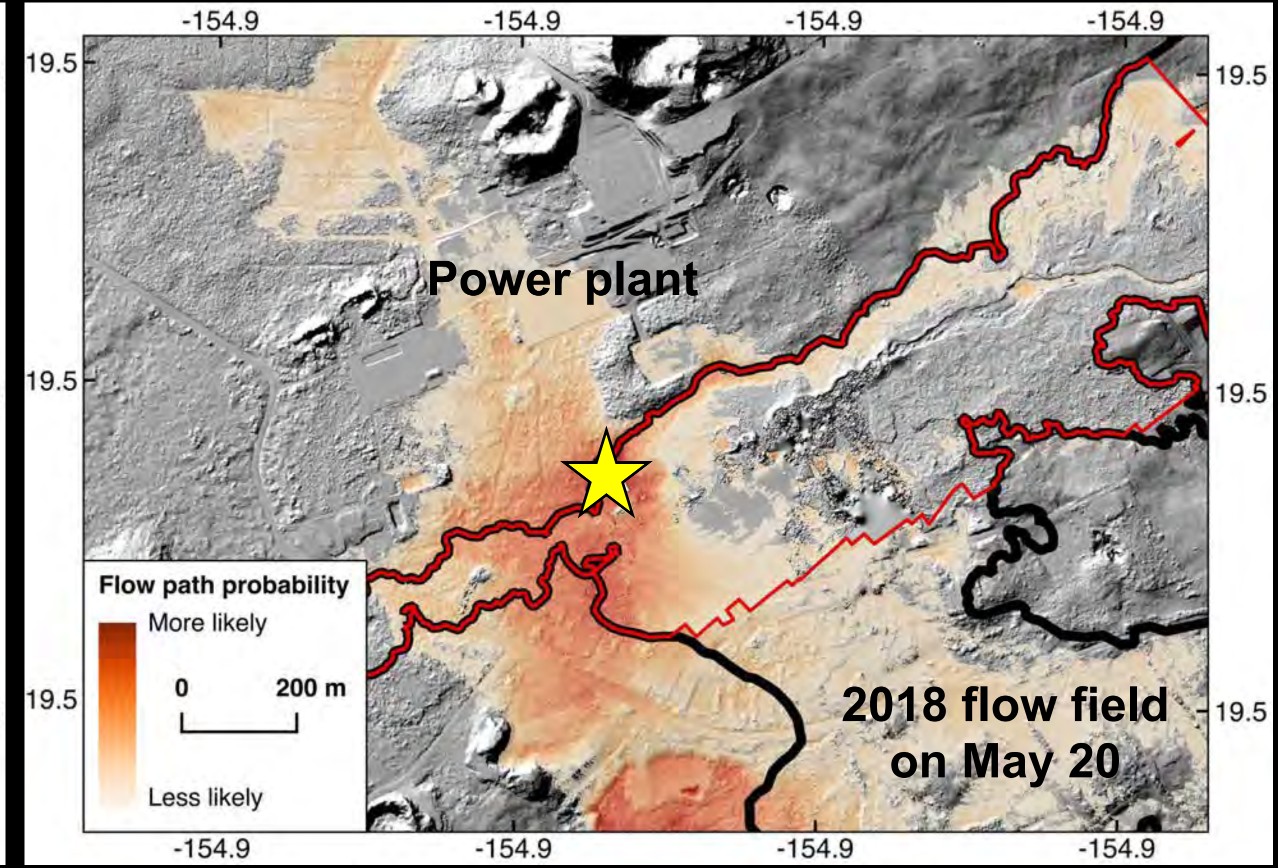
USGS science for a changing world

Lava flow forecasting

As flows are emplaced, updated topography is needed!



Pre-eruptive lidar



Pre-eruptive lidar + May 21, 2018 UAS DSM

Some knowledge gaps requiring topographic data

- What is the scale of topography required for accurate hazard forecasts?
- How does vegetation cover, or other surface features, impact volcano flows?
- How do volcanic landforms (craters, cones, flows) evolve through time?
- How does landform morphology reflect eruption dynamics? Material properties?
- How can syn-eruptive topographic change best inform real-time volcanic hazard assessment?

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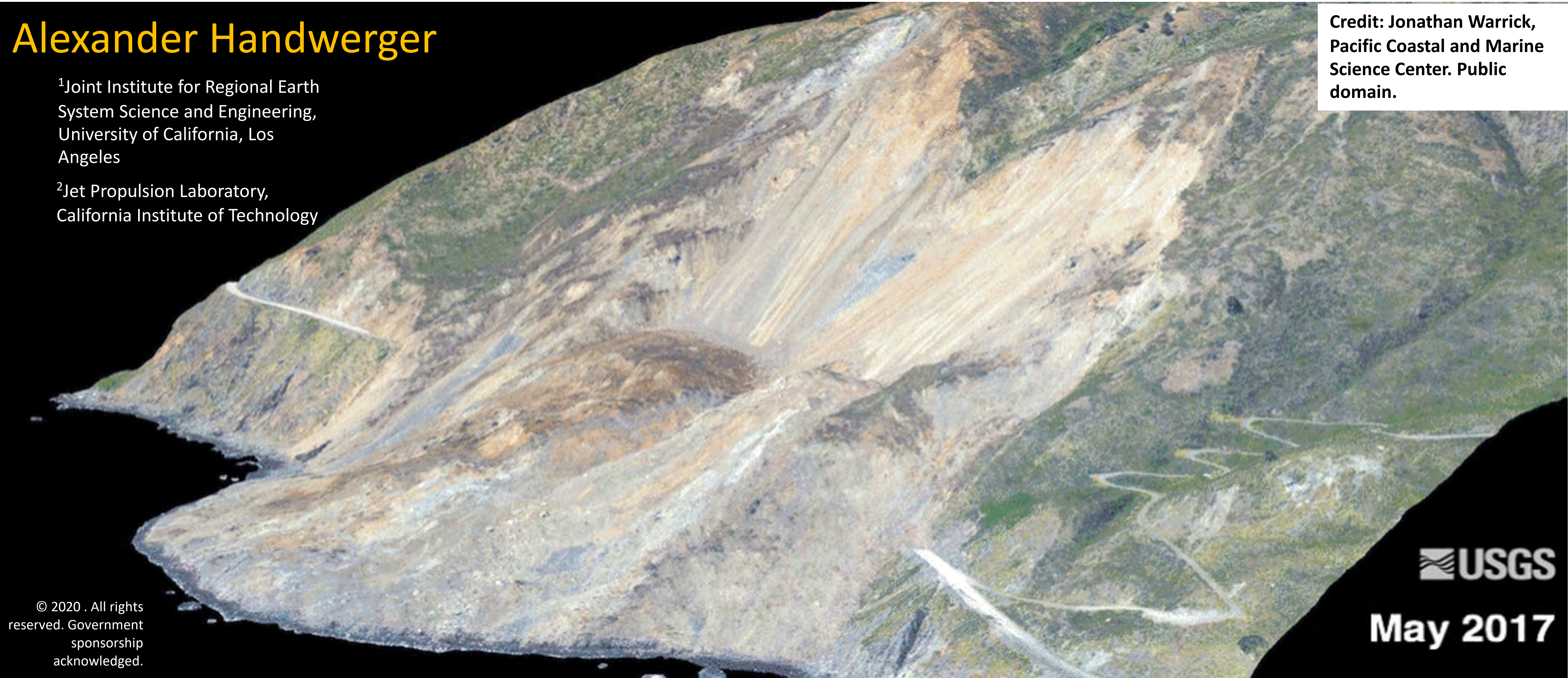
Repeat Surface Topography and Vegetation (STV) observations for landslide applications

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Alexander Handwerger

[1]Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles

[2]Jet Propulsion Laboratory, California Institute of Technology



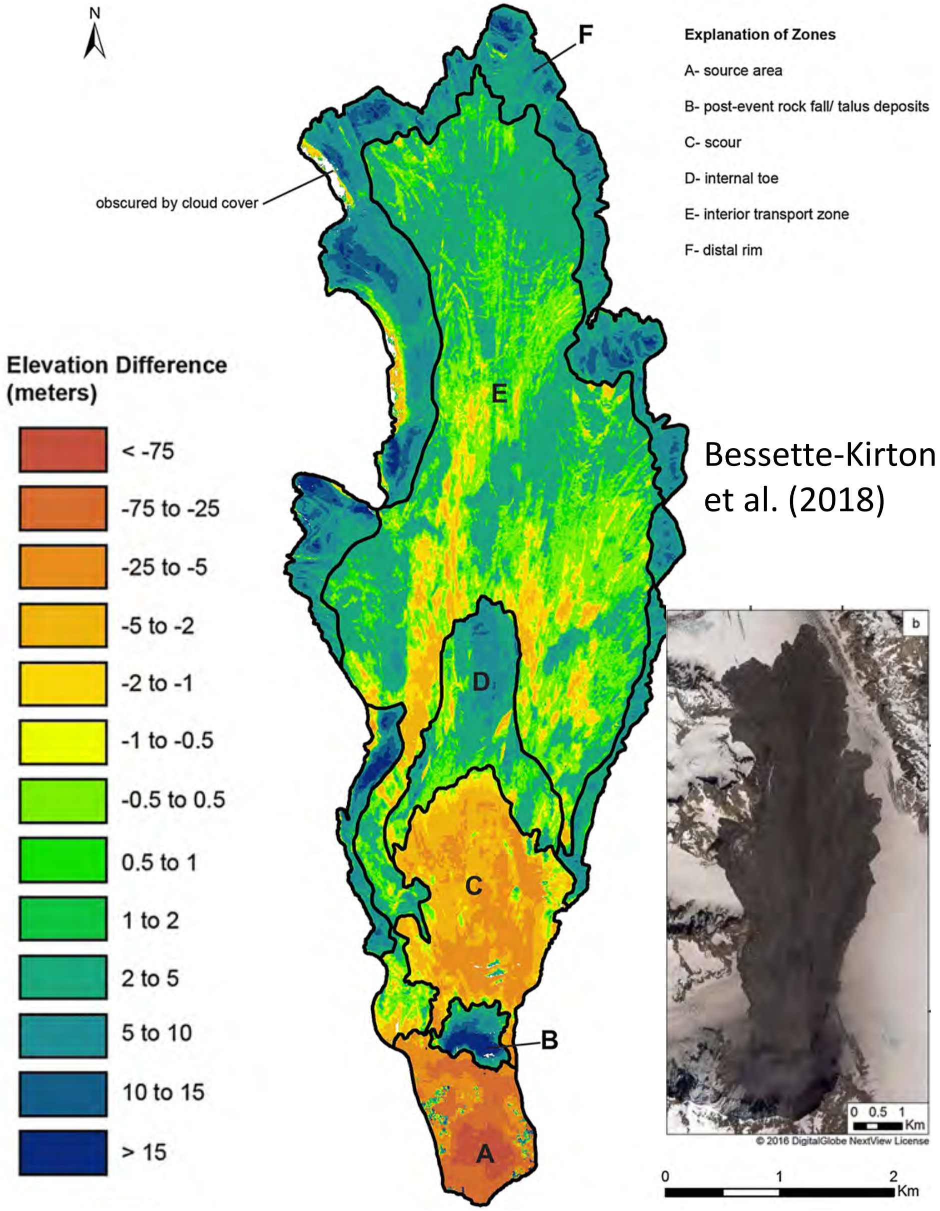
Credit: Jonathan Warrick, Pacific Coastal and Marine Science Center. Public domain.

A few ways repeat STV observations can be used for landslide applications

- <u>Landslide geometry</u>: Use repeat STV to measure geometry of landslides
  - Accurate measurements of area, thickness, volume
  - Hazardous impact and erosion

2016 Lamplugh Rock Avalanche, Alaska

WorldView DEMs (2 m pixel)



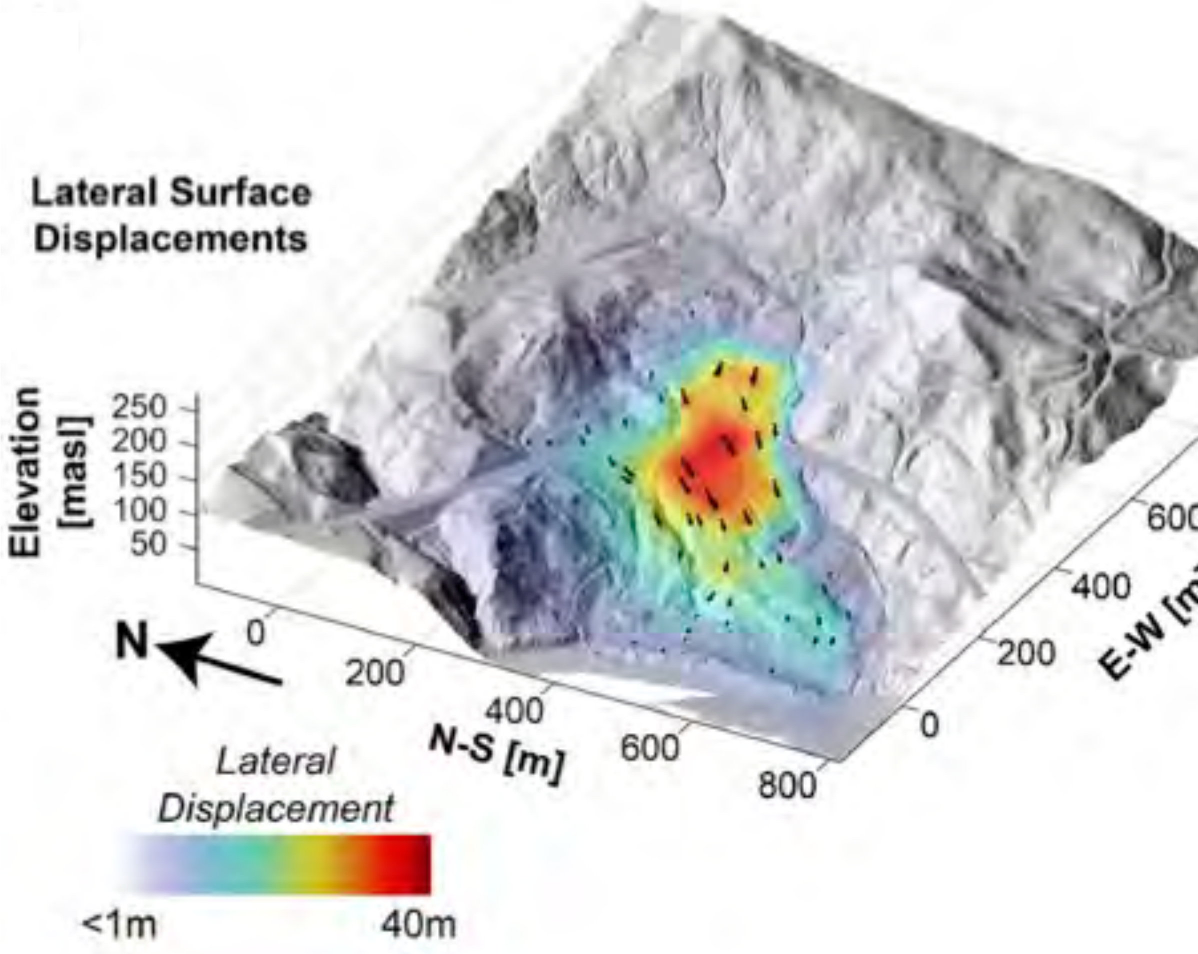
Bessette-Kirton et al. (2018)

A few ways repeat STV observations can be used for landslide applications

- Landslide geometry: Use repeat STV to measure geometry of landslides
  - Accurate measurements of area, thickness, volume
  - Hazardous impact and erosion
- Kinematics: Use repeat STV to document 3D surface changes at high spatial resolution.
  - Infer controls on motion by comparing to environmental forcings
  - Develop and test landslide models

2019 Hooskanaden Landslide, Oregon, USA

terrestrial lidar (2018) and UAS lidar (2019)

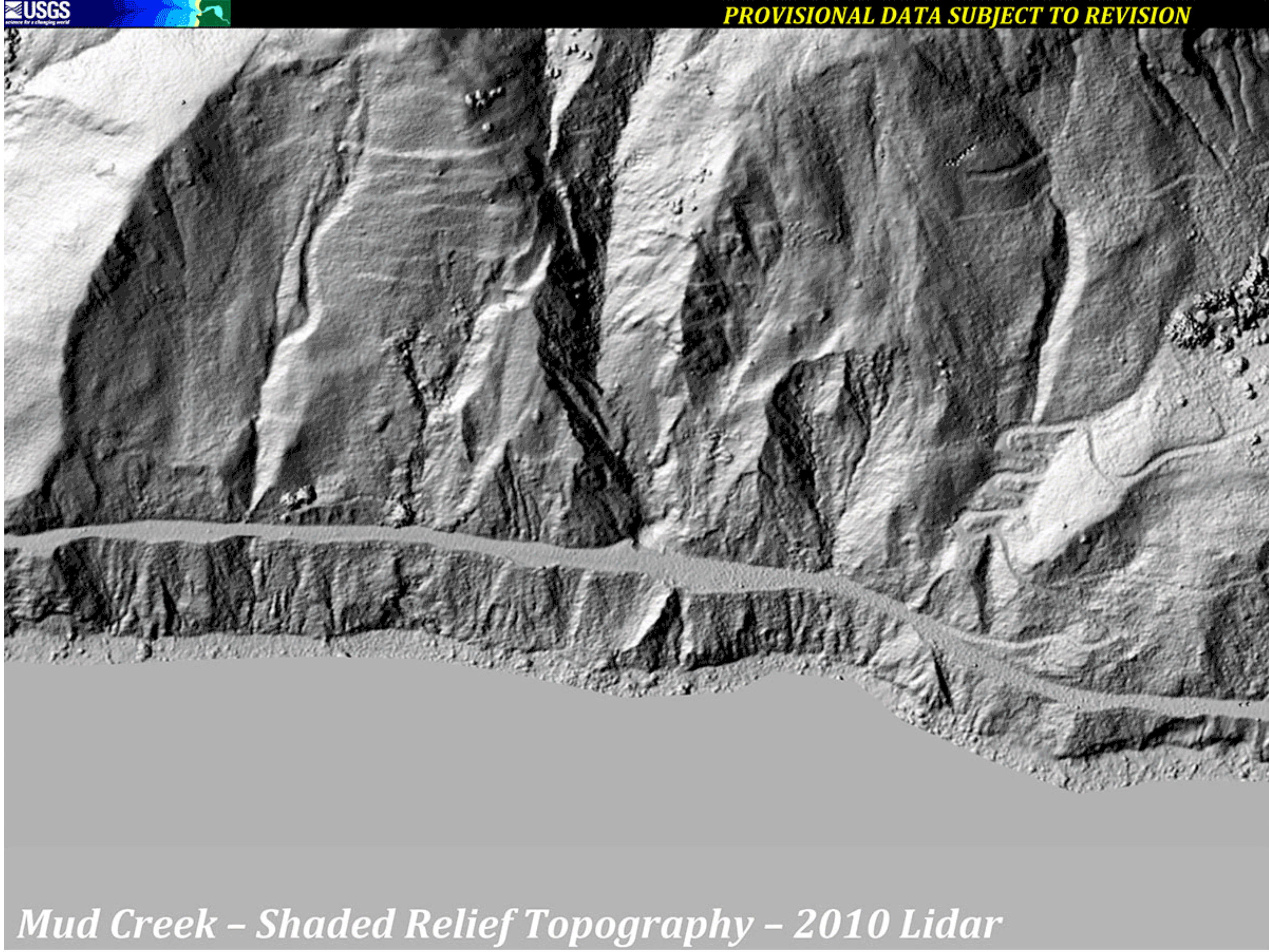


Alberti et al. 2020

Case study: Mud Creek landslide, California, USA

- Failed catastrophically on May 20, 2017
- Destroyed CA Highway 1
- Highway was closed for ~1 yr and 2 months
- Repair cost ~$54 million
- Volume = ~3 million m^3 of material

- Repeat lidar and structure from motion (SfM) reveal complex landslide history and geometry!



Credit: Jonathan Warrick, Pacific Coastal and Marine Science Center. Public domain.

Warrick et al. 2019

1 m grid

Case study: Mud Creek landslide, California, USA

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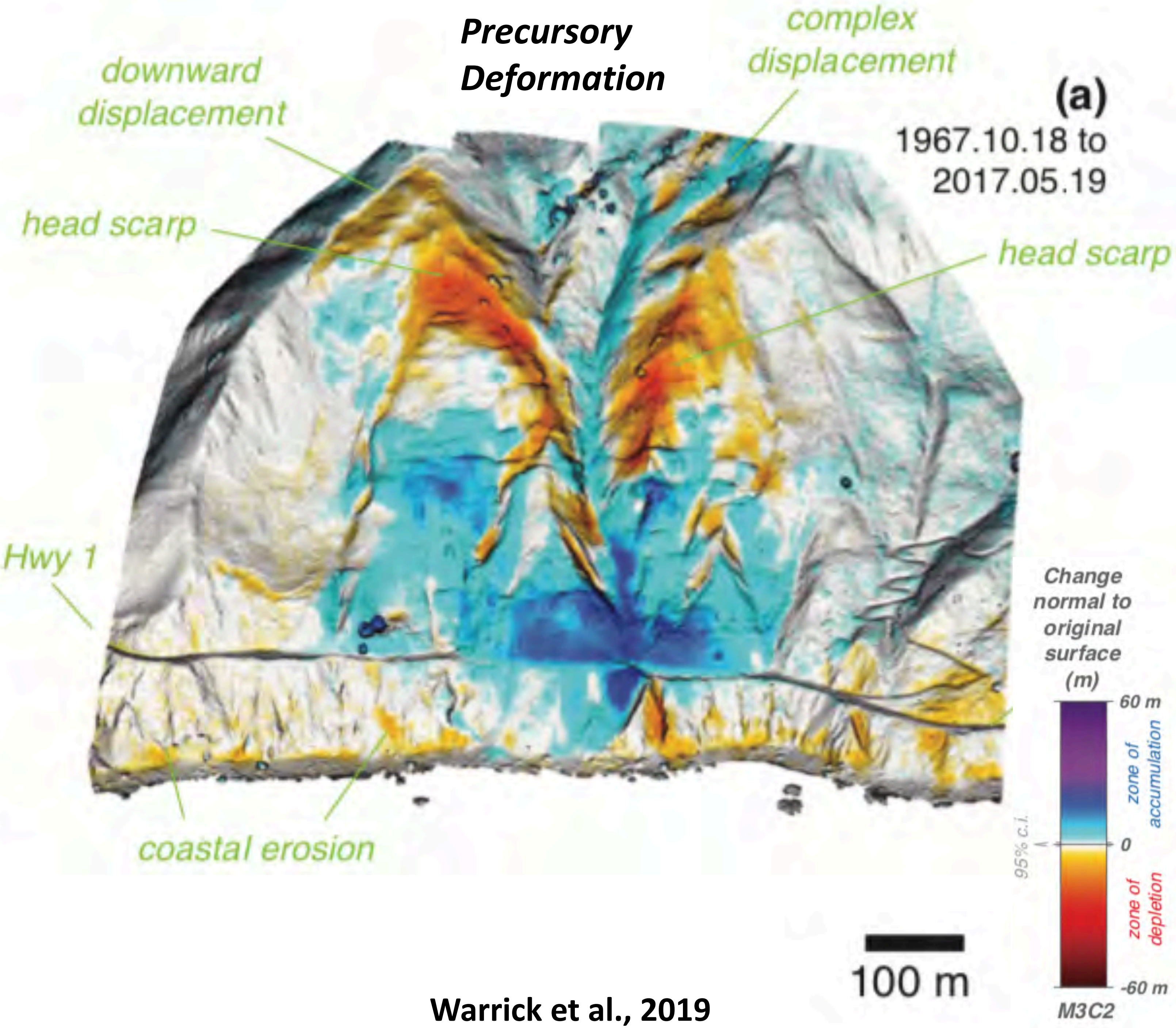
Precursory Deformation



Warrick et al., 2019

Case study: Mud Creek landslide, California, USA

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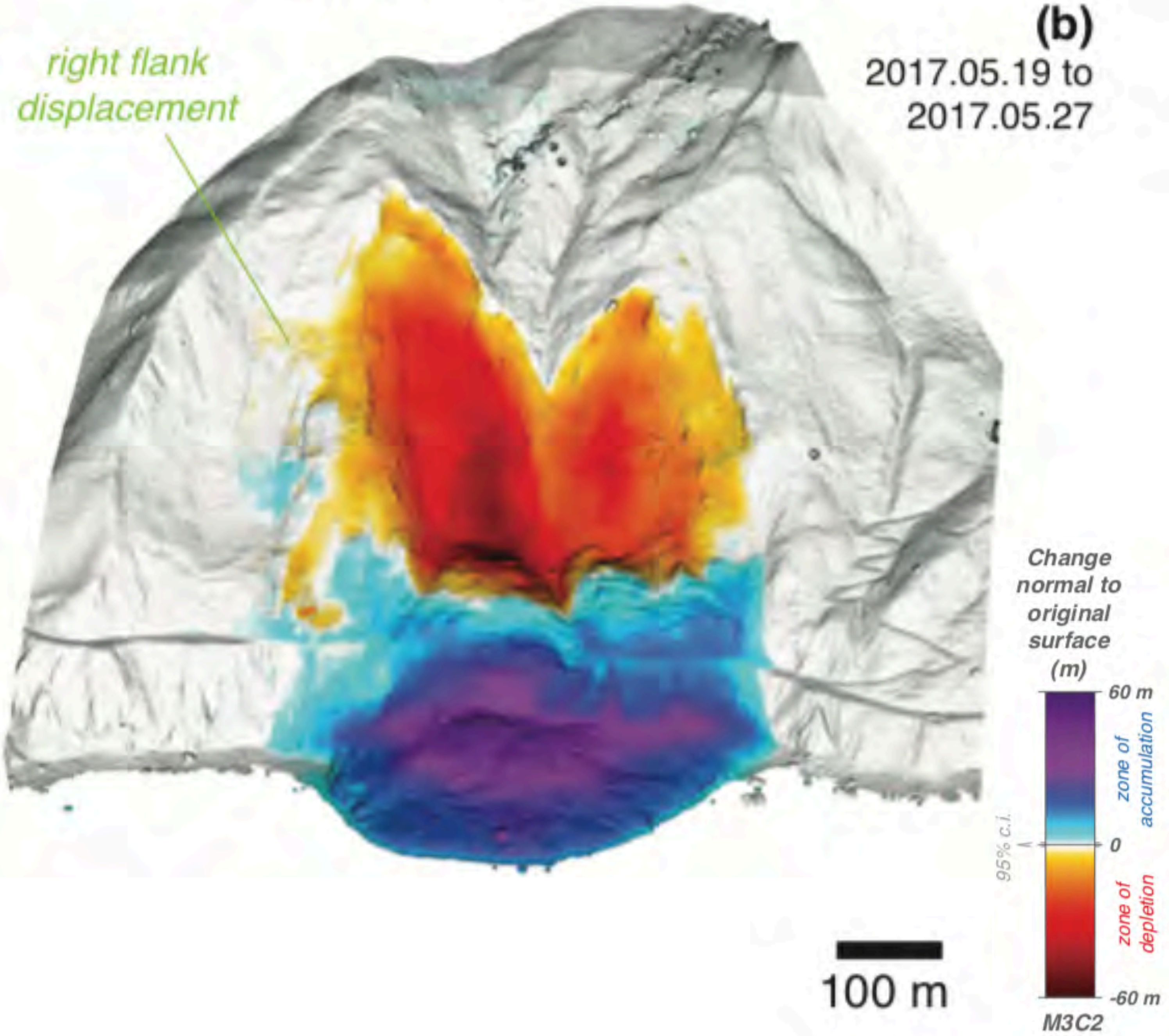
Catastrophic Failure

Warrick et al., 2019



Case study: Mud Creek landslide, California, USA

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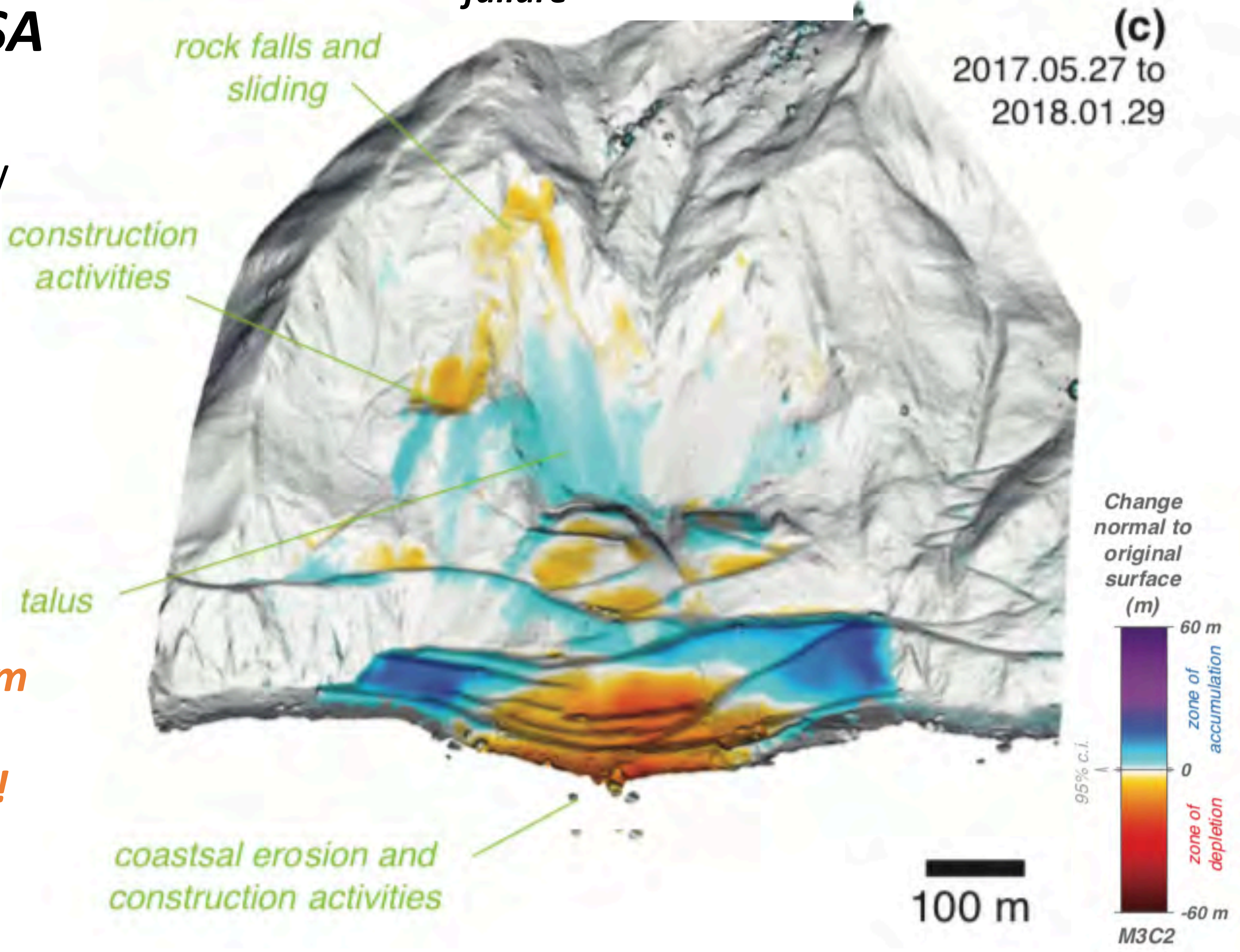
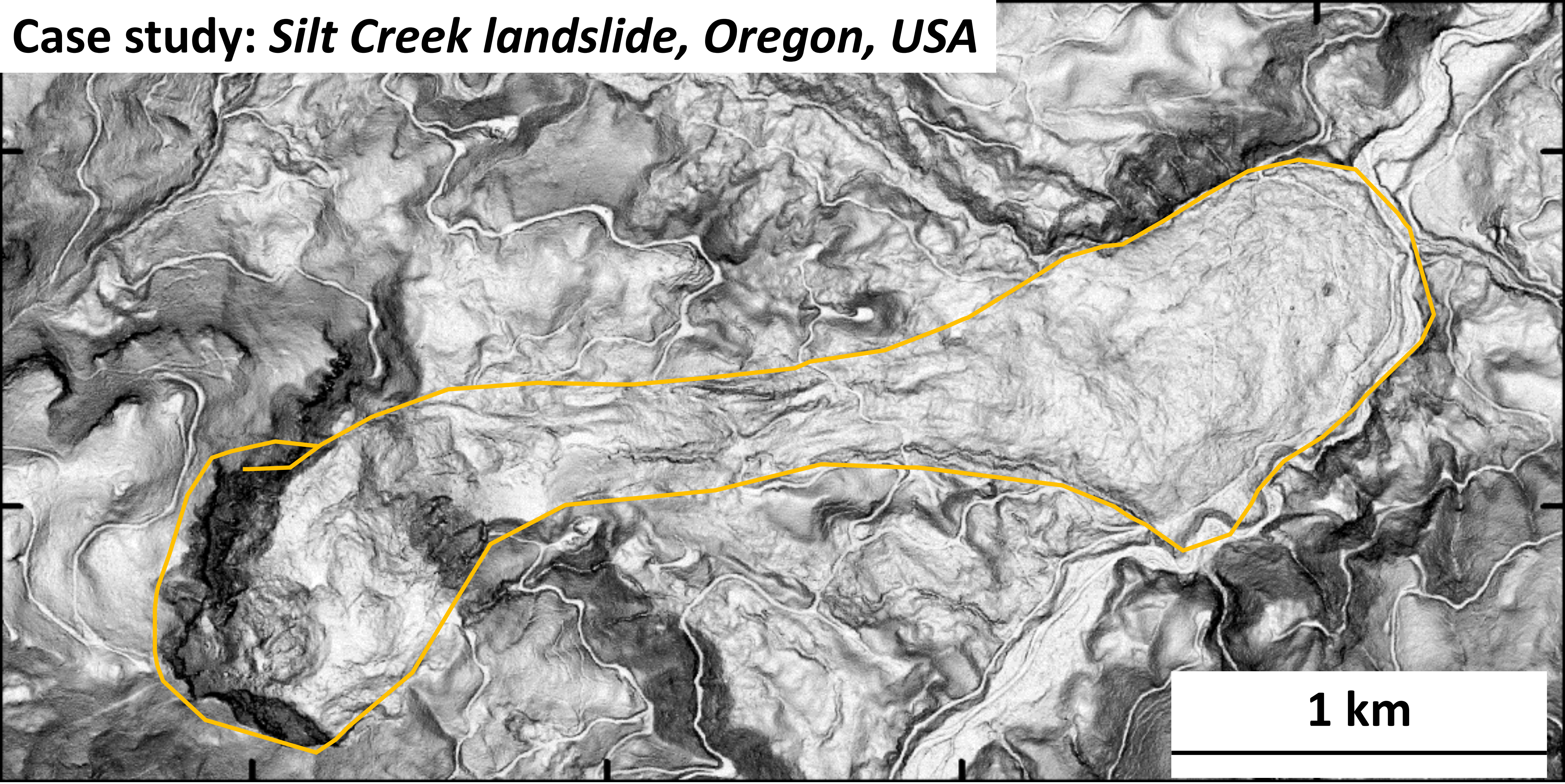
Post-catastrophic failure

Warrick et al., 2019



Case study: *Silt Creek landslide, Oregon, USA*

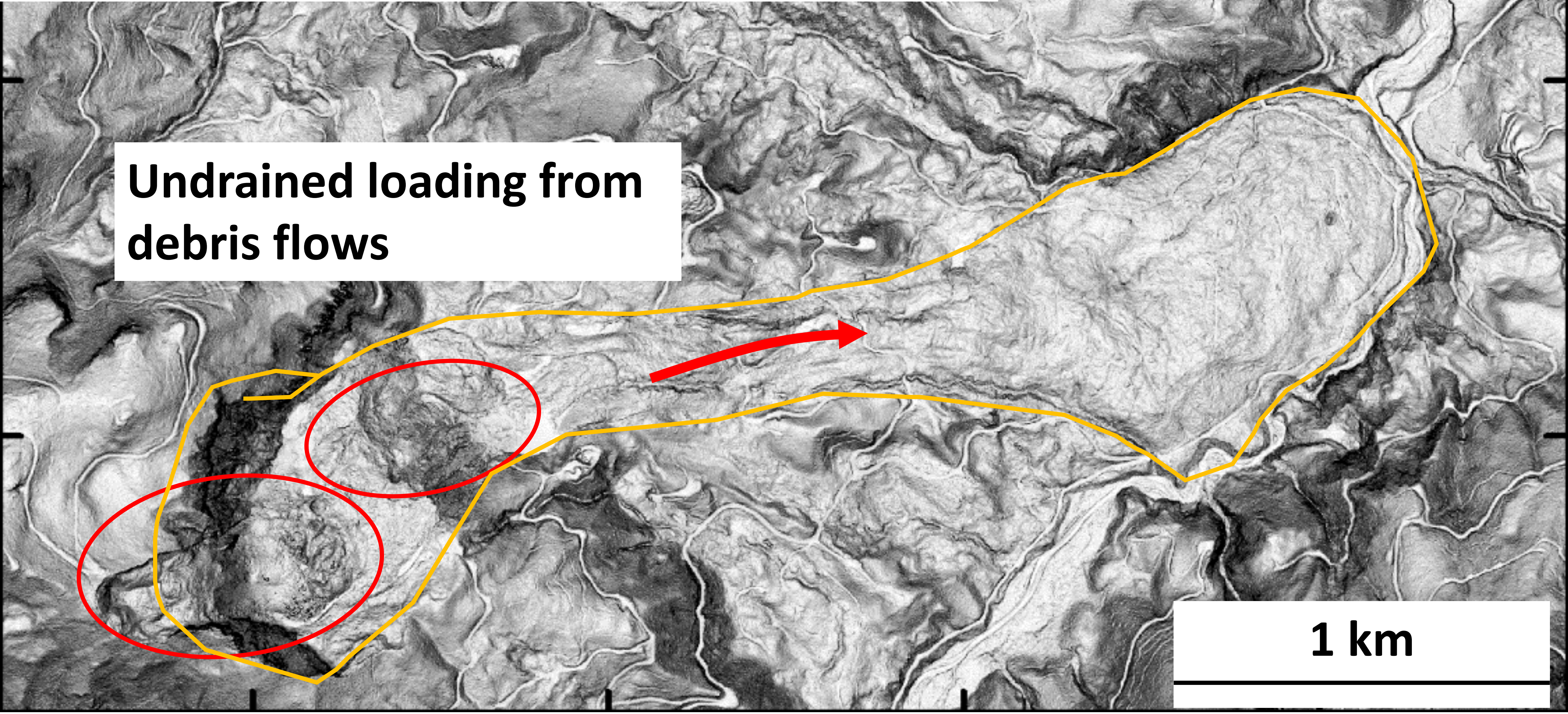


Lidar - 1 m resolution,
3D surface displacement field:

2012 **2015**

Booth et al., 2018
Slide courtesy of A. Booth

Case study: *Silt Creek landslide, Oregon, USA*



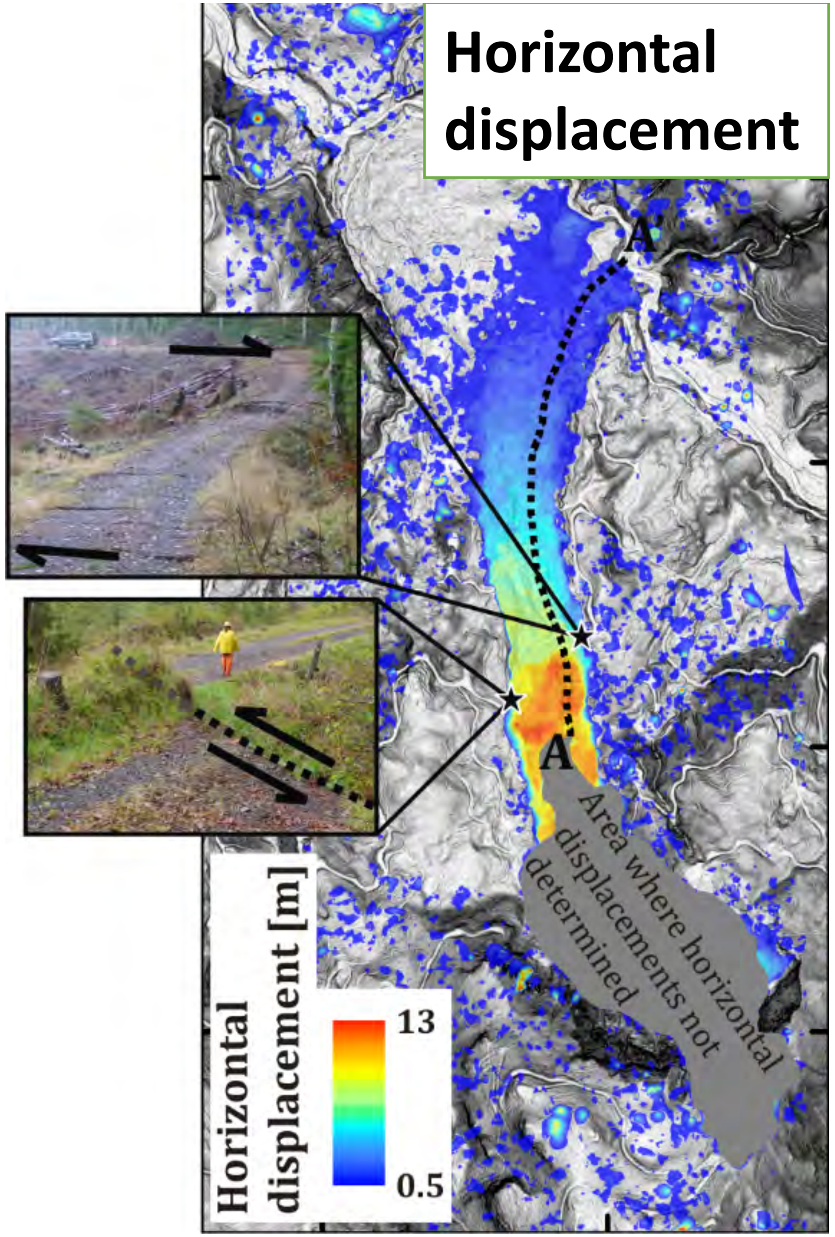
Undrained loading from debris flows

Lidar - 1 m resolution,
3D surface displacement field:

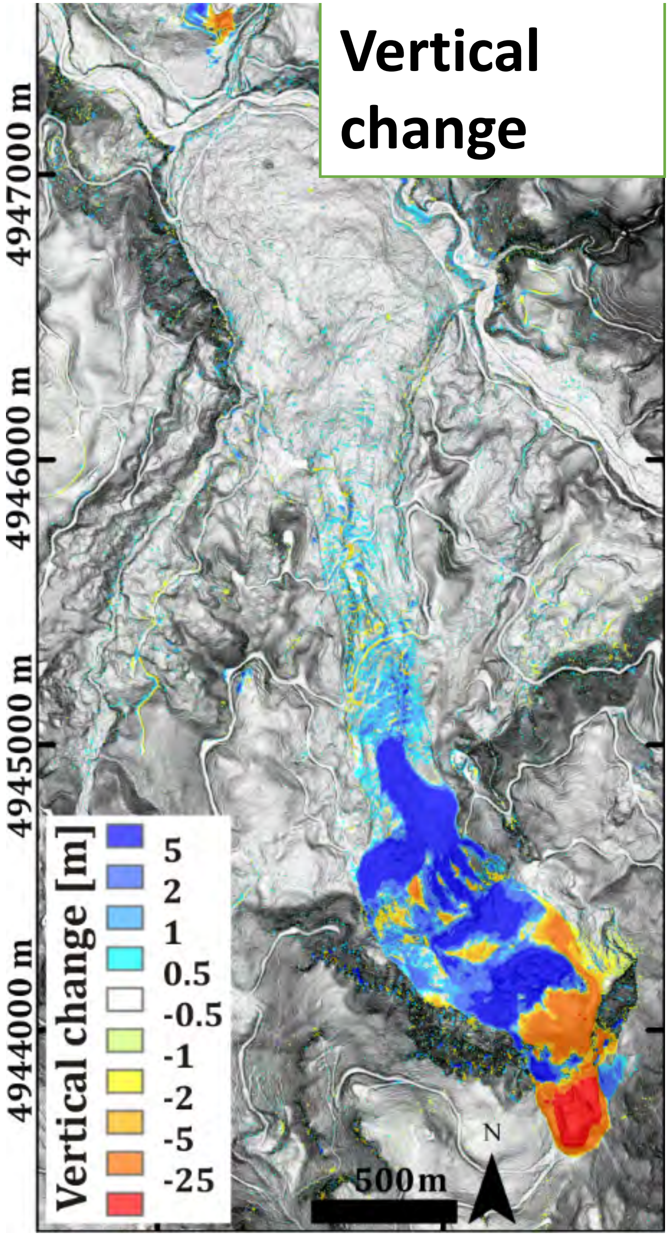
2012 2015

Booth et al., 2018
Slide courtesy of A. Booth

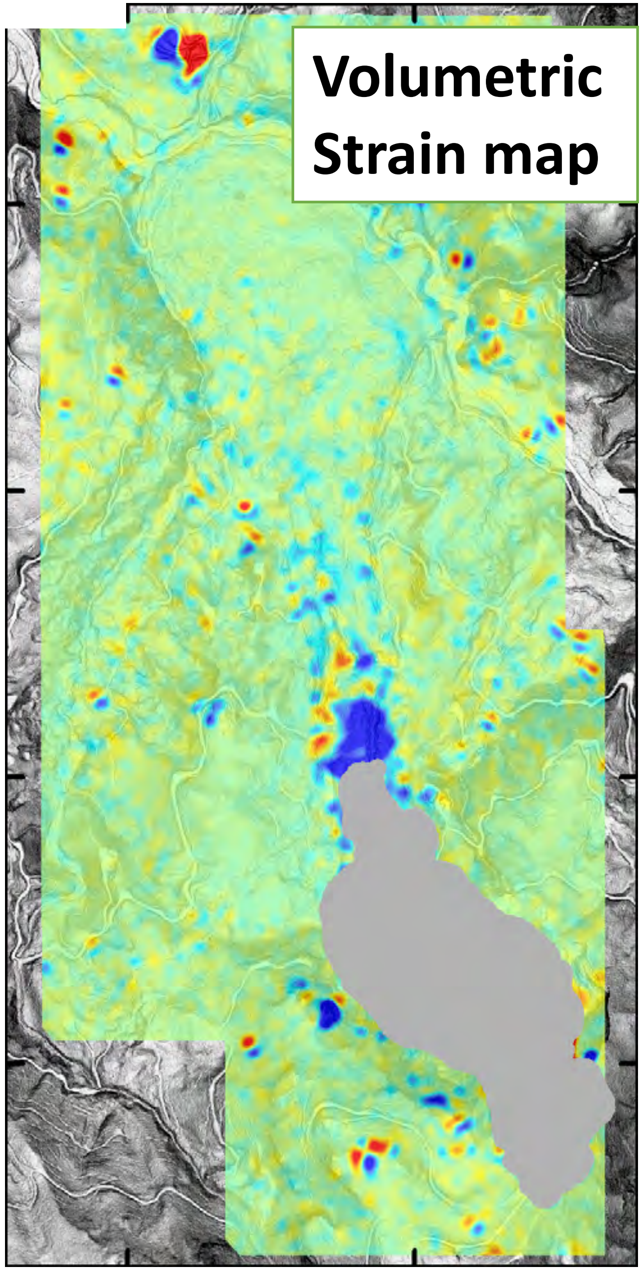
Case study: *Silt Creek landslide, Oregon, USA*



Horizontal displacement



Vertical change



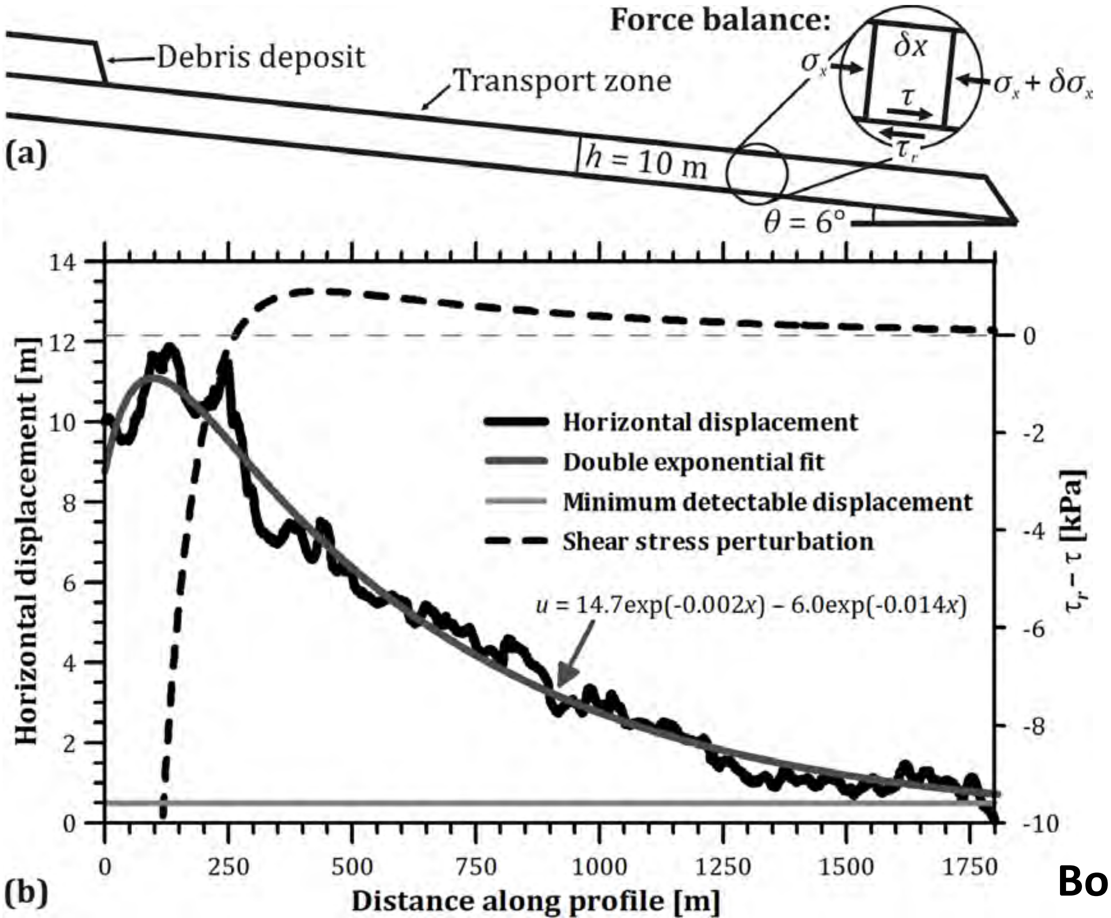
Volumetric Strain map

Booth et al., 2018

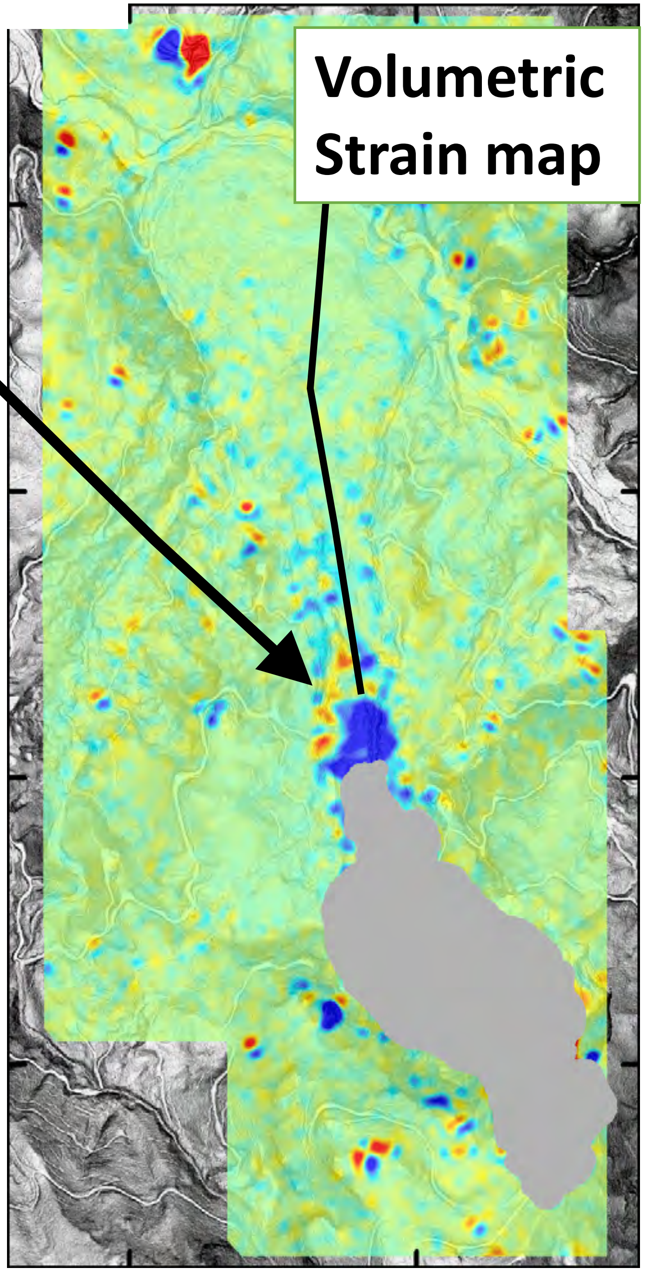
Slide courtesy of A. Booth

Case study: *Silt Creek landslide, Oregon, USA*

- 10-20% volumetric dilation
- Evidence of negative dilatancy-pore pressure feedback restraining motion
- Convex-up displacement profile predicts ~1 kPa strengthening



Booth et al., 2018

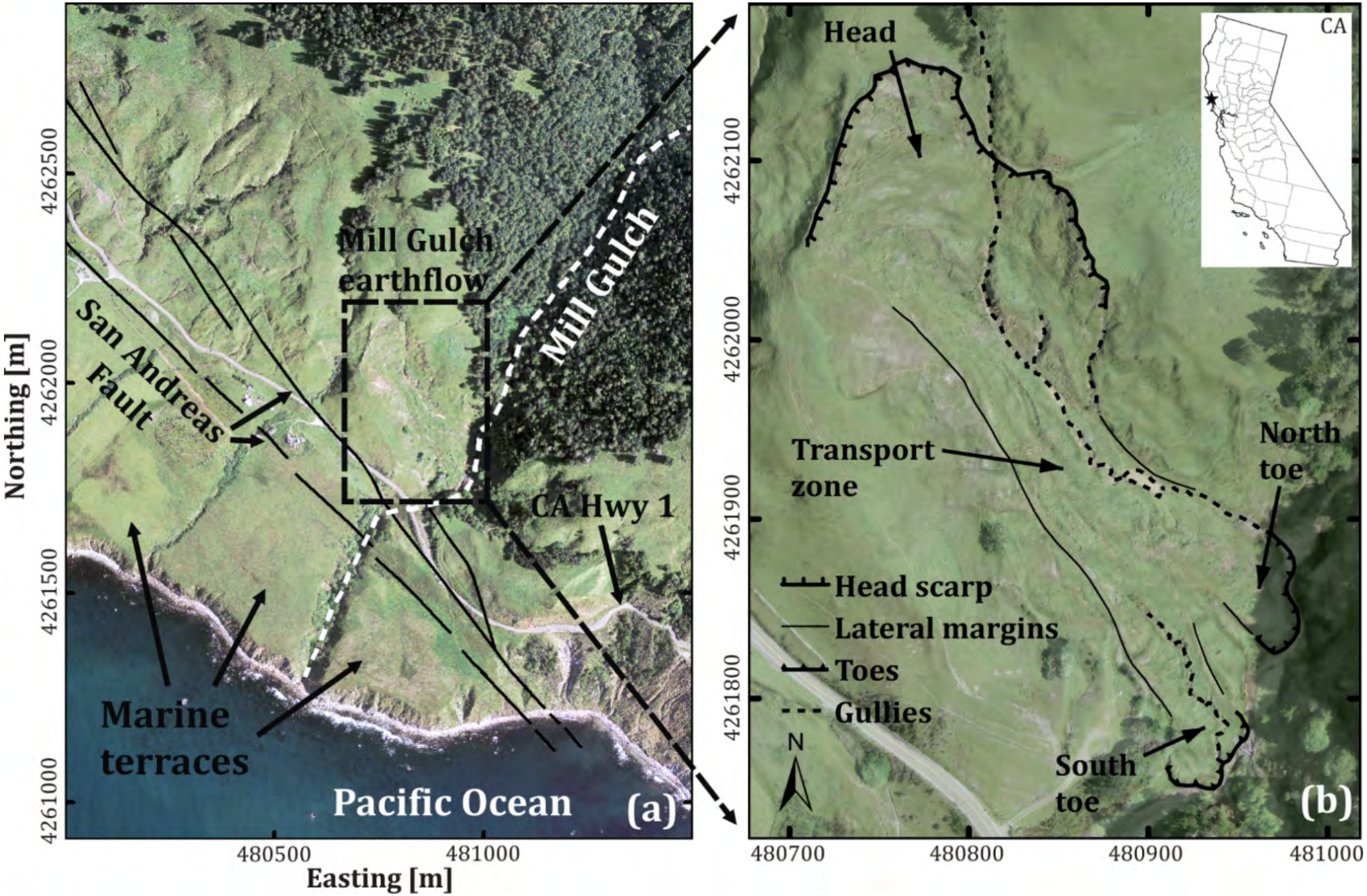


Volumetric Strain map

Slide courtesy of A. Booth

Case study: Mill Gulch earthflow, California, USA

- 400 m long earth slide-flow
- Bowl-shaped head, narrow transport zone, and a “forked” toe
- Next to San Andreas Fault (surface rupture in 1906)
- Earthflow causes 0.3 mm/yr erosion averaged over Mill Gulch catchment [*DeLong et al.*, 2012]
- ***Landslide motion is driven by rainfall***



Booth et al., 2020

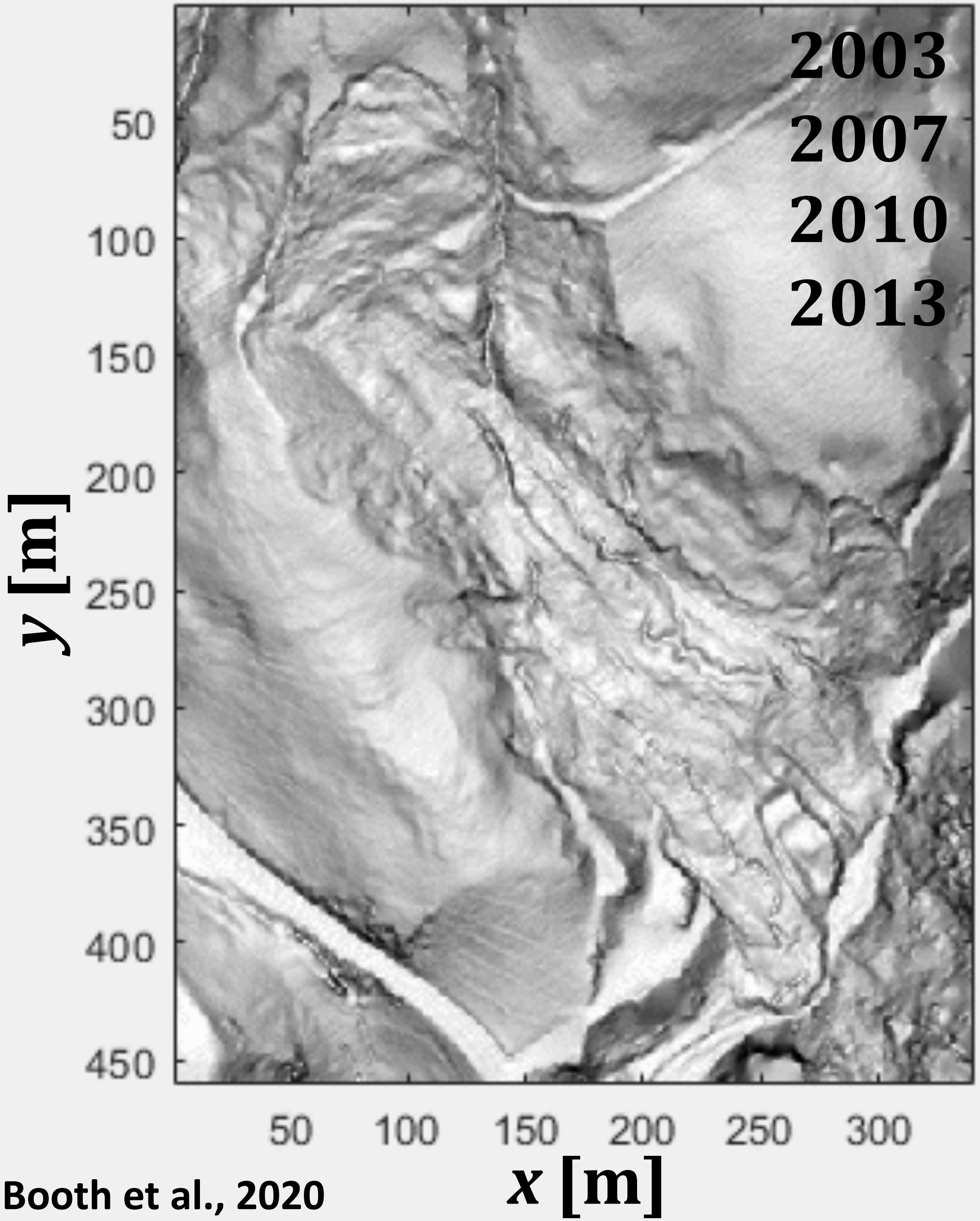
Slide courtesy of A. Booth

Case study: Mill Gulch earthflow, California, USA

- Airborne lidar from 2003, 2007, 2010, and 2013
- Surface displacements of up to several tens of meters over this time period
- Displacement pattern highly variable in both space and time

1 m pixel

Slide courtesy of A. Bo

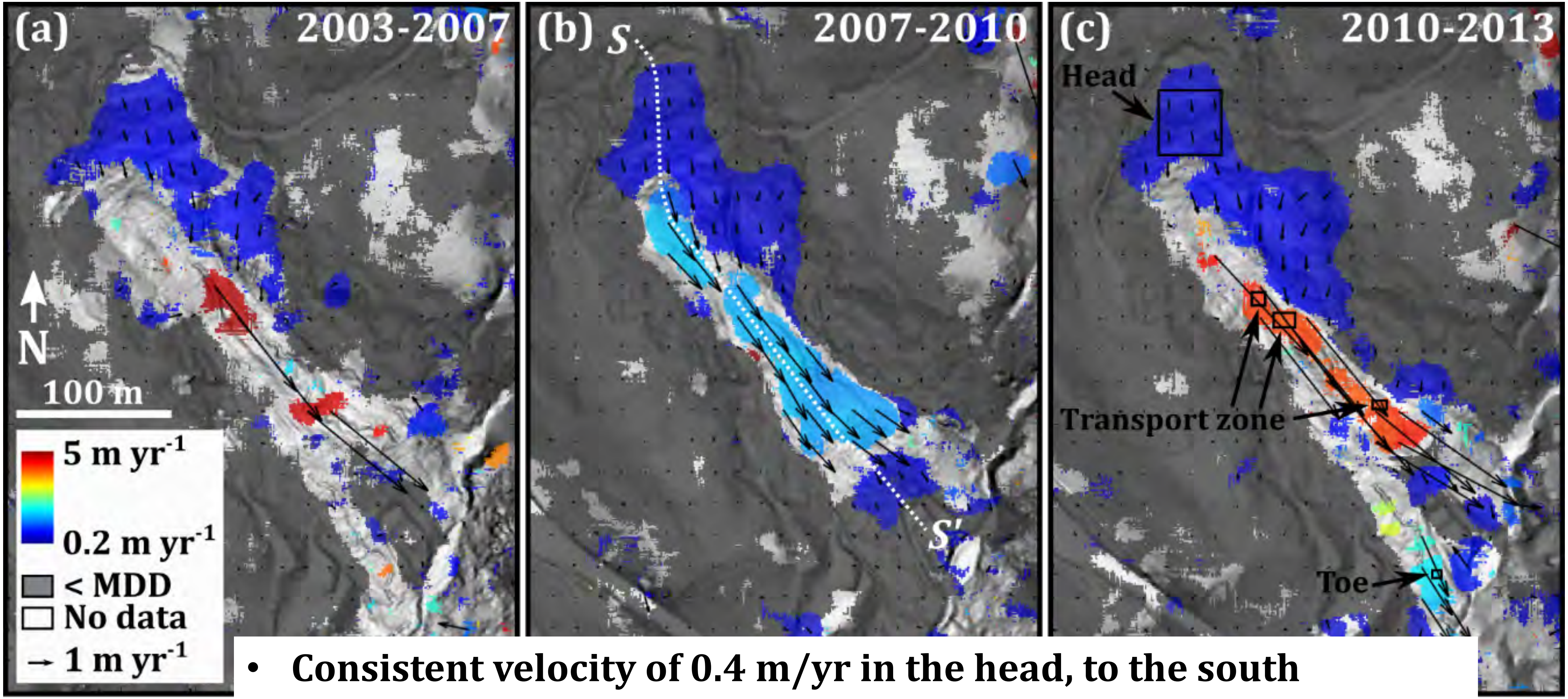


Booth et al., 2020

Slide courtesy of A. Booth

Horizontal displacements

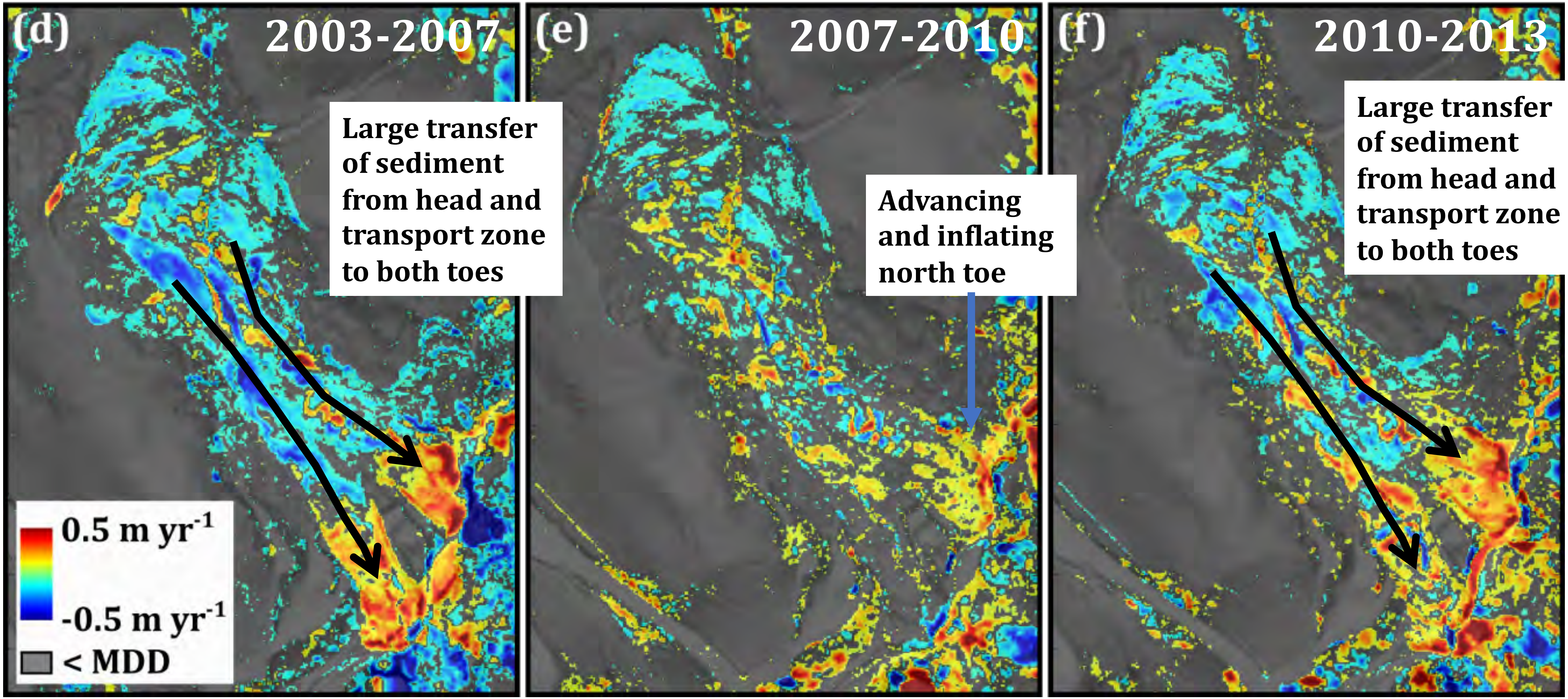
Booth et al., 2020



- Consistent velocity of 0.4 m/yr in the head, to the south
- Faster velocities of 2-5 m/yr in transport zone, to the southeast
- Moderate and variable velocities of 0-4 m/yr in south toe

Vertical changes

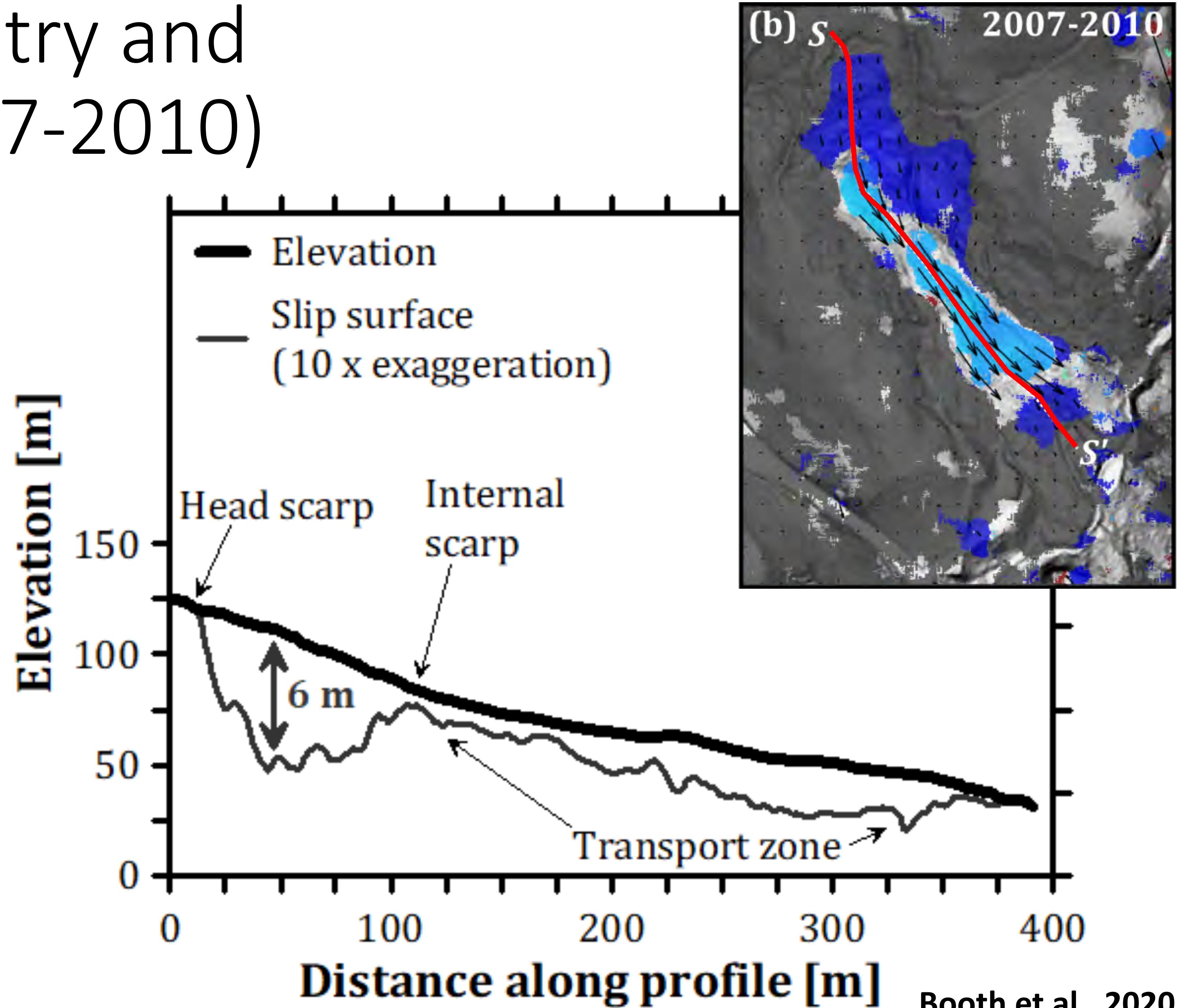
Booth et al., 2020



Slide courtesy of A. Booth

Slip surface geometry and sediment flux (2007-2010)

- Invert the continuity equation to predict landslide thickness that is consistent with 3D surface displacements [*Booth et al.*, 2013; *Delbridge et al*., 2016]
- 6 m deep rotational failure in the head
- Shallow (<2 m deep) and variable transport zone



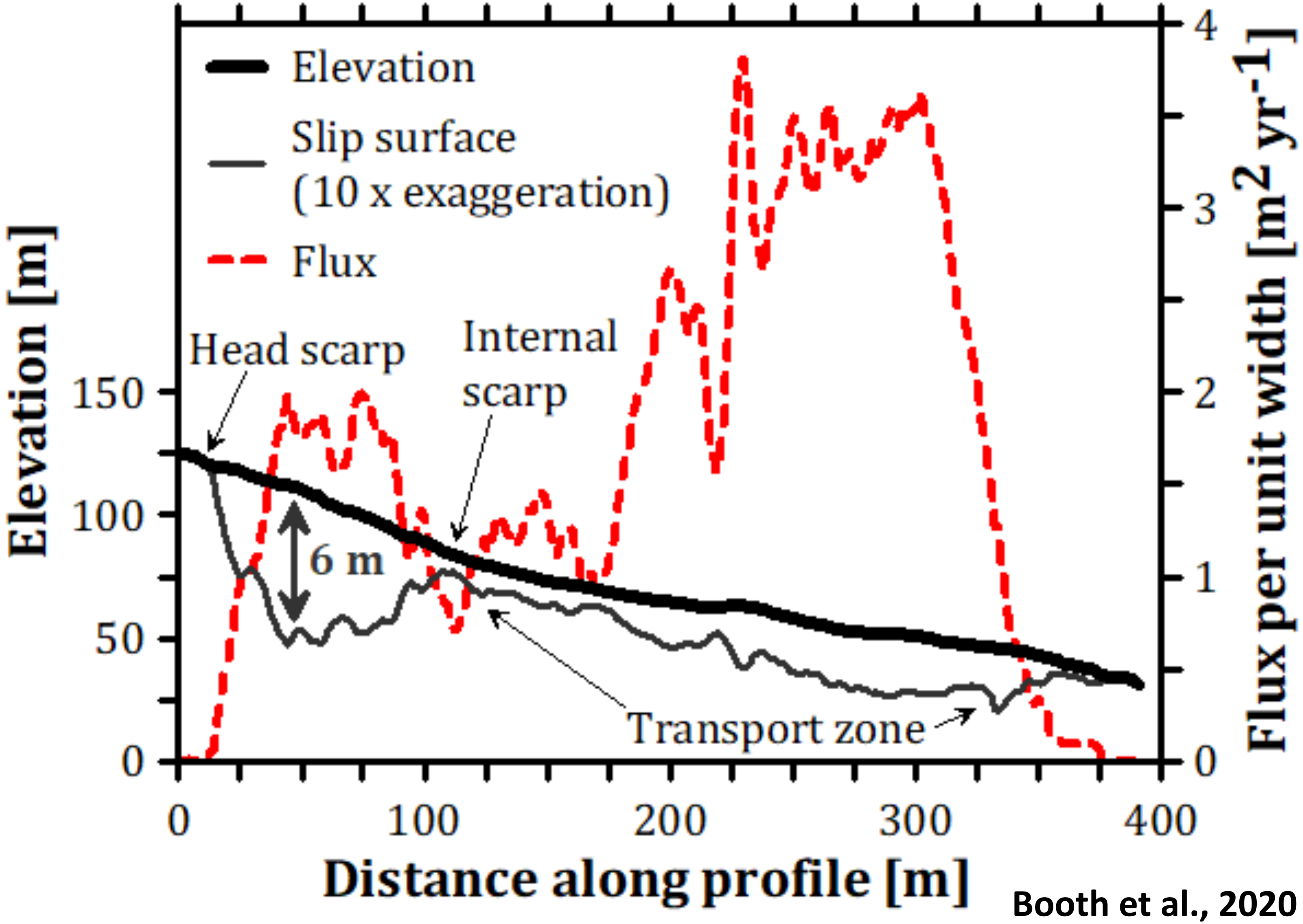
Booth et al., 2020

Slide courtesy of A. Booth

Slip surface geometry and sediment flux (2007-2010)

Slide courtesy of A. Booth

- Invert the continuity equation to predict landslide thickness that is consistent with 3D surface displacements [*Booth et al.*, 2013; *Delbridge et al.*, 2016]
- 6 m deep rotational failure in the head
- Shallow (<2 m deep) and variable transport zone
- Nonsteady earthflow flux: local surges where sediment flux is high



Booth et al., 2020

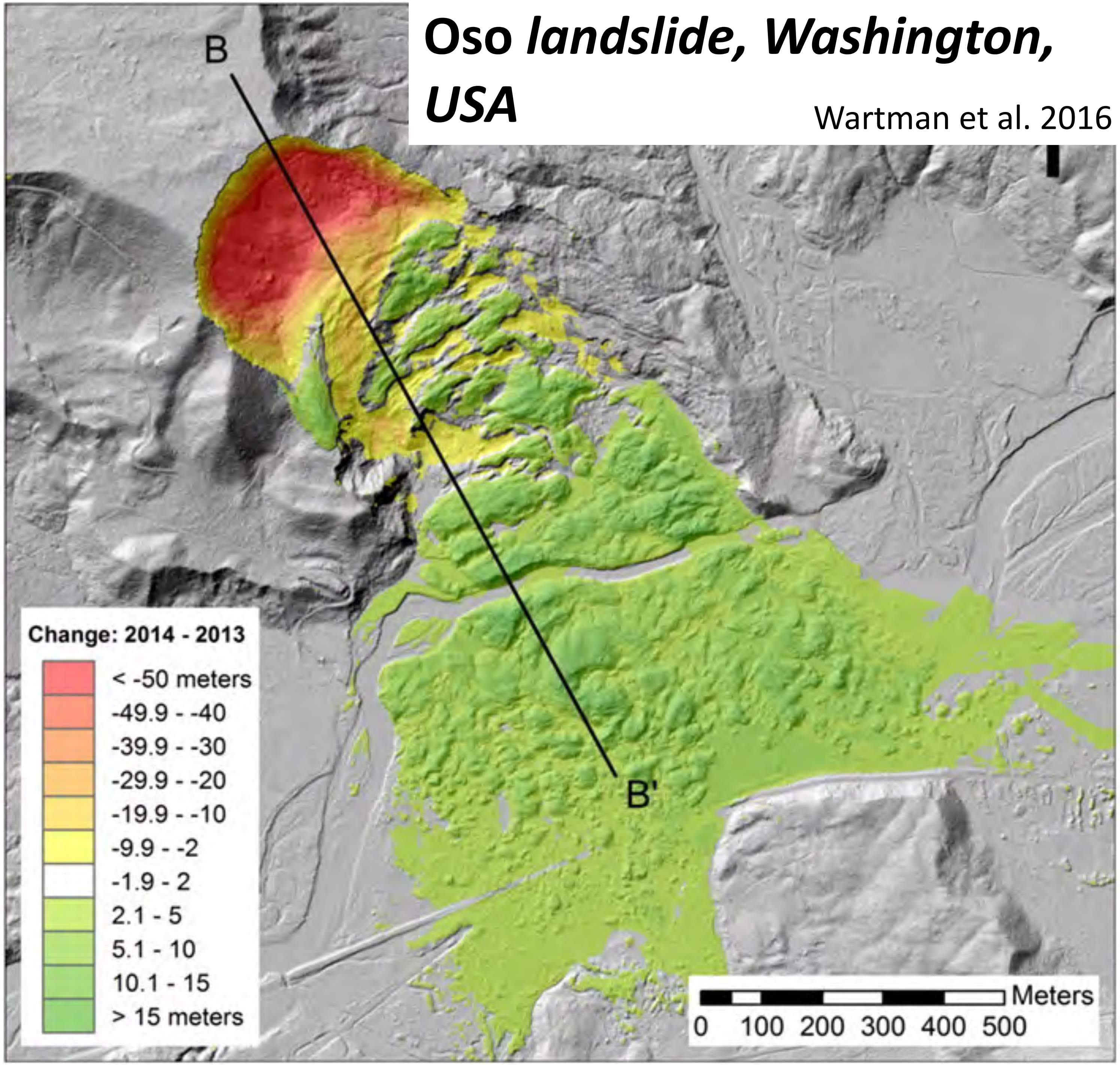
Oso *landslide, Washington, USA*

Summary

- Repeat STV is important for landslide monitoring
- Track 3D change with high resolution and full spatial coverage
- Provides key information on the landslide geometry and kinematics

Knowledge gaps

- What mechanisms explain landslide variability?
- How does sediment flux vary within and between landslides?
- What does the landslide subsurface look like? Especially for slow-moving landslides
- **Use repeat data to monitor precursory landslide displacements that precede catastrophic failure and for urgent response following catastrophic collapse.**



Wartman et al. 2016

Three of the Four Main Decadal Survey Questions Concerning Sea Level:

C-1. ***How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?***

S-3. ***How will local sea level change along coastlines around the world in the next decade to century?***

C-6. ***Can we significantly improve seasonal to decadal forecasts of societally relevant climate variables?***

Sea level has risen by **3.1 ± 0.3 mm/yr** since 1993 and that the rate has accelerated by **0.084 ± 0.025 mm/yr^2** (Dieng et al., 2017; Nerem et al., 2018; WCRP Global Sea Level Budget Group, 2018).

Relative sea level depends on global mean sea-level rise and its regional variations, vertical land motion, and other local processes, such as small-scale currents, wind, waves, fresh water input from river estuaries, shelf bathymetry, and along-shore and cross-shore sediment transport (e.g., Woodworth et al., 2019; National Academies, 2020).

CIRES

Vertical Land Motion and Sea Level Rise at Coastal Megacities

Michael J. Willis, Eduard R. Heijkoop, R. Steven Nerem & Kristy F. Tiampo
University of Colorado Boulder
Mike.Willis@Colorado.Edu

Future inundation at coastal locations dependent on:

- **Amount and rate of sea level rise**
- **Vertical Land Motion**
- **Topography**

Baulk et al., 2008

~650 Million people in low elevation zones
~390 Million live in coastal cities
This population is exploding.

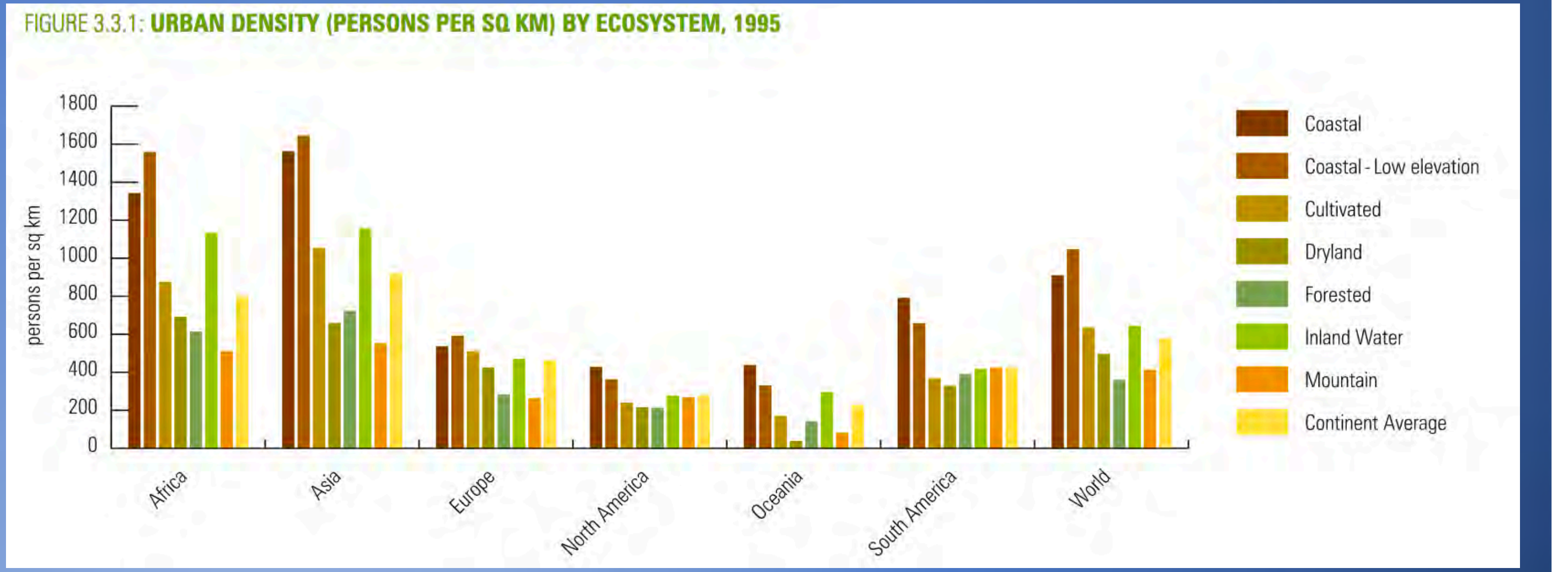
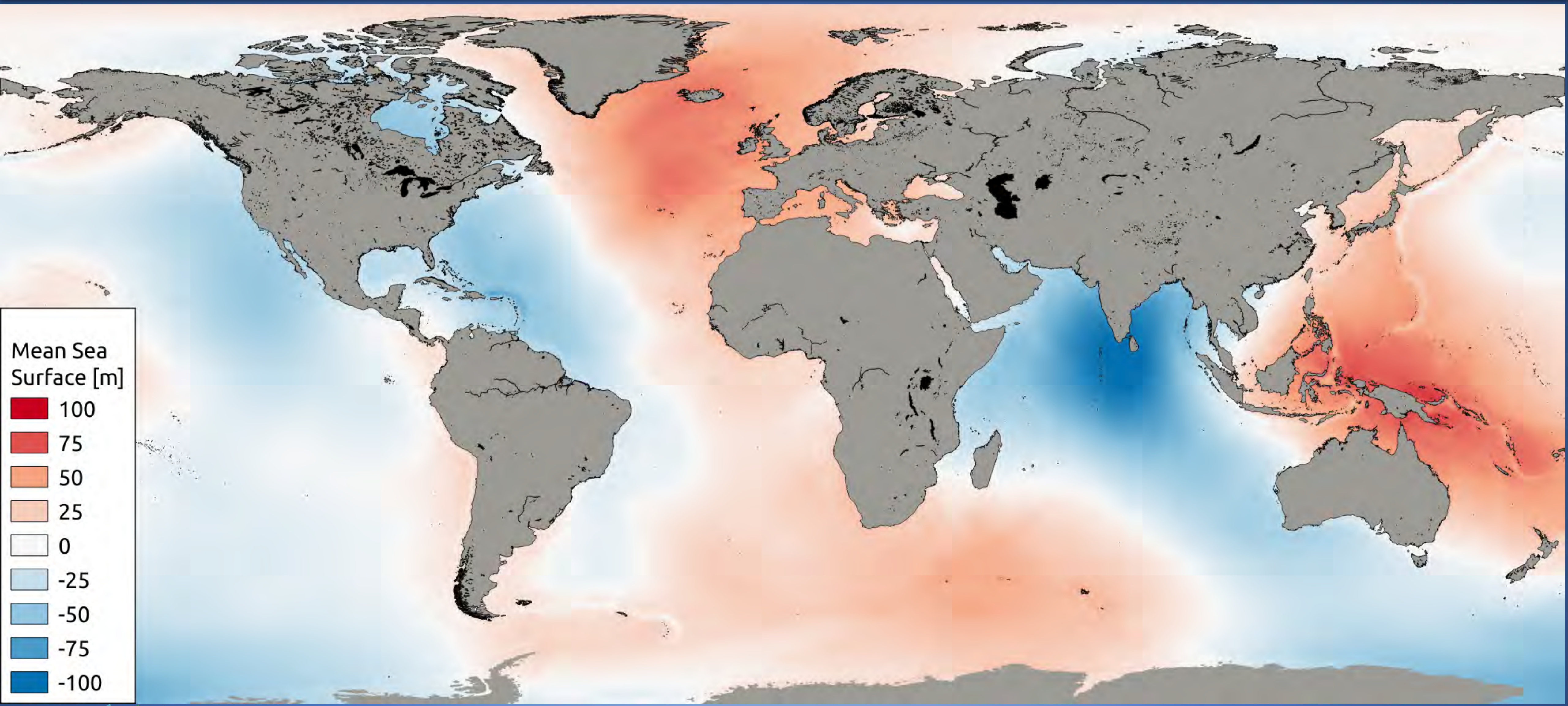


FIGURE 3.3.1: URBAN DENSITY (PERSONS PER SQ KM) BY ECOSYSTEM, 1995

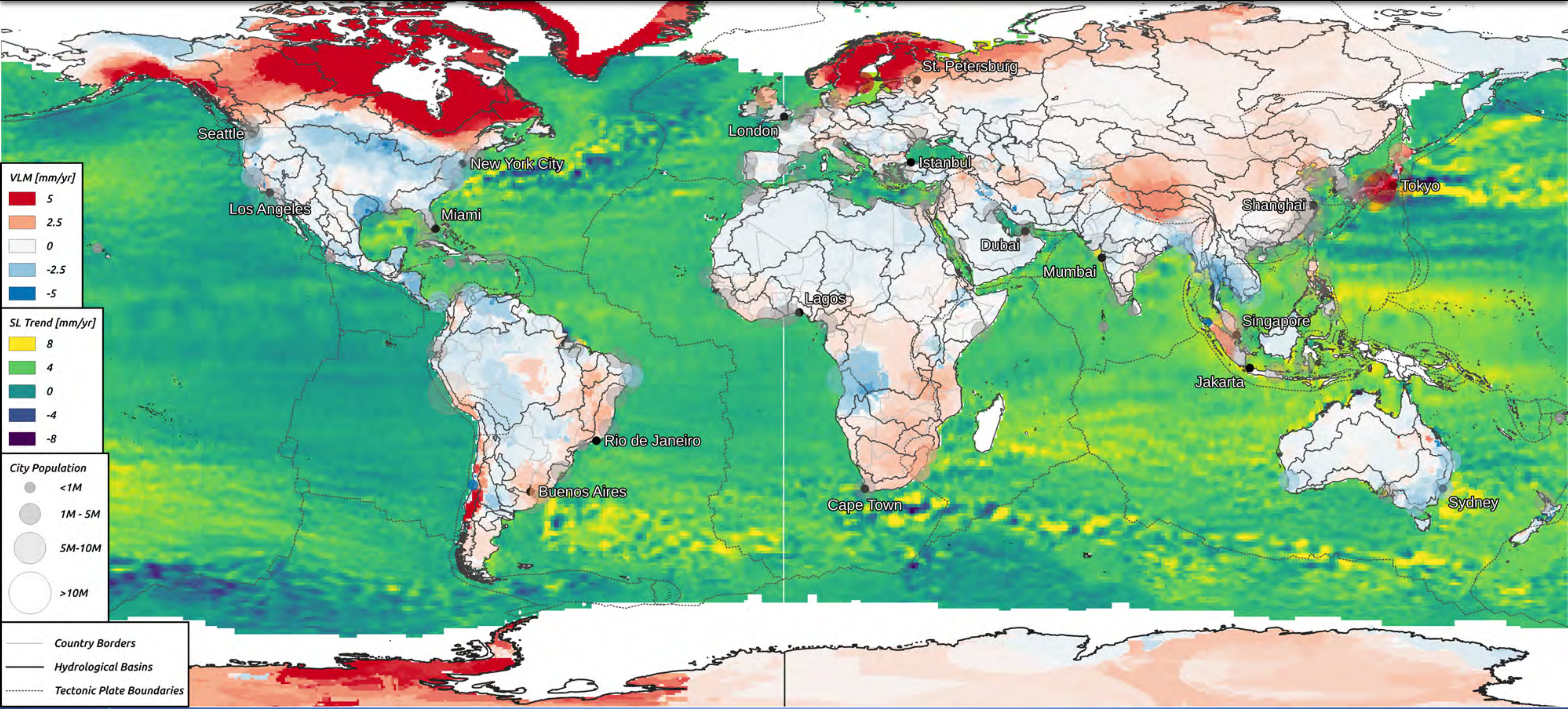
Distribution of Tide Gauges (Not Good)

Sources: Esri, Earthstar Geographics

DTU18 Mean Sea Surface Model (WGS84)

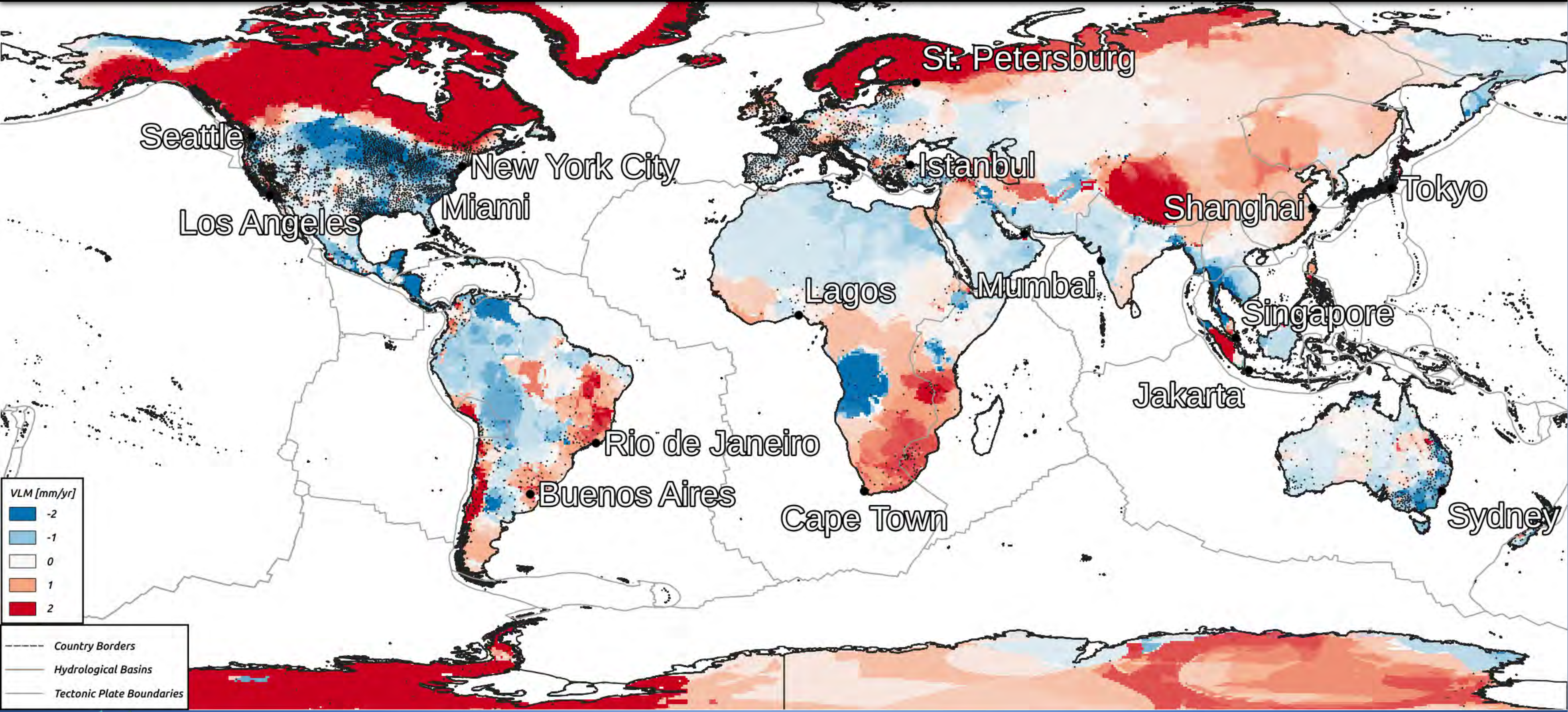


Sea Surface Trend + Vertical Land Motion



VLM from Bill Hammond and Geoff Blewitt

Distribution of GNSS sites (Not Good)



Vertical Land Motion driven by:

Tectonics
Extraction of groundwater or hydrocarbons
Glacial Isostatic Adjustment
Sediment compaction

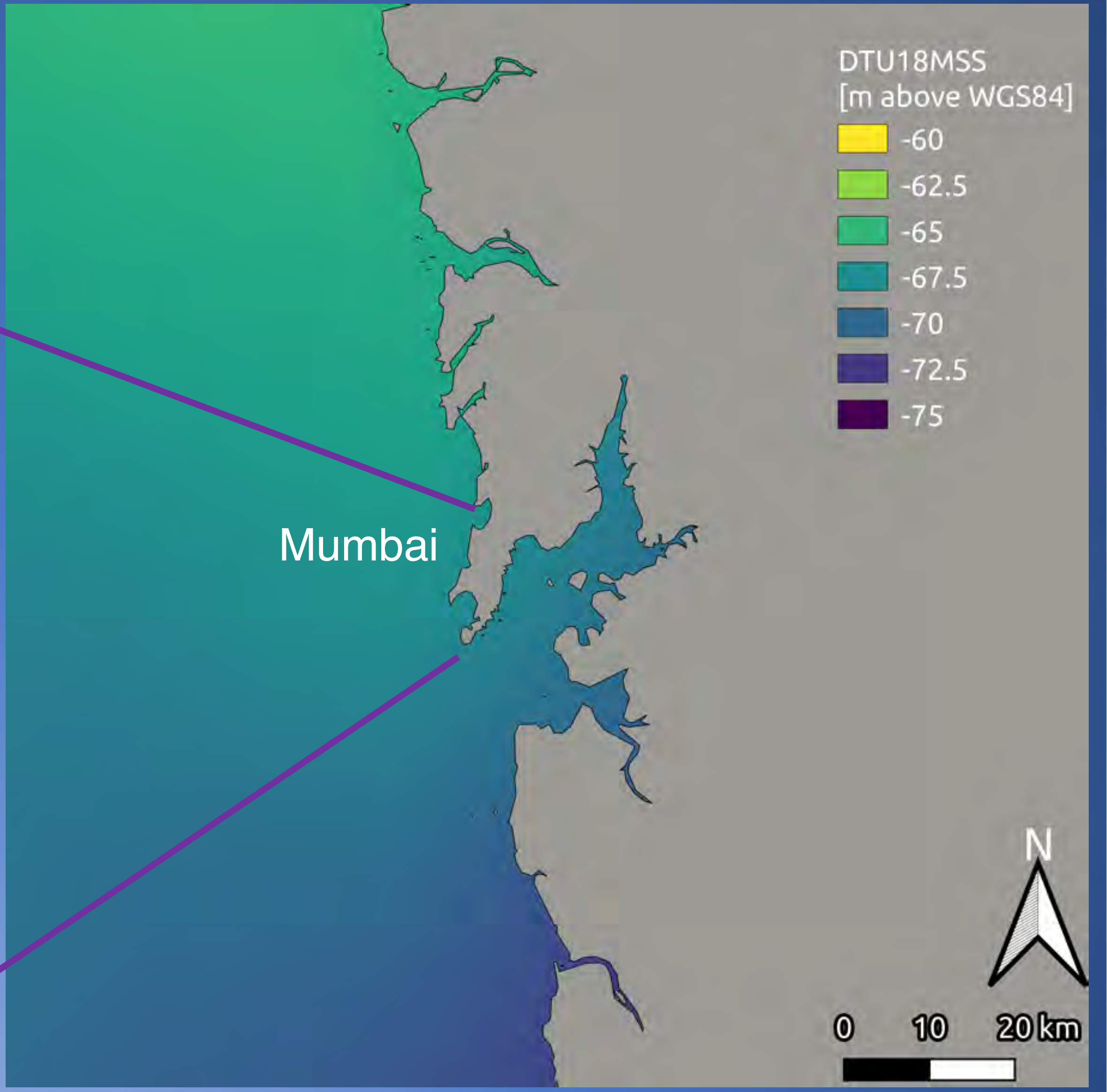
Focus on Mumbai, India

Mumbai is built on fill, between several islands.

26 Million people in metro area.

1843

British Library/Flikr



Use Optical Derived DSMs, InSAR, GNSS, Global Mean Sea Level Observations, Tidal Observations and Storm models to predict inundation

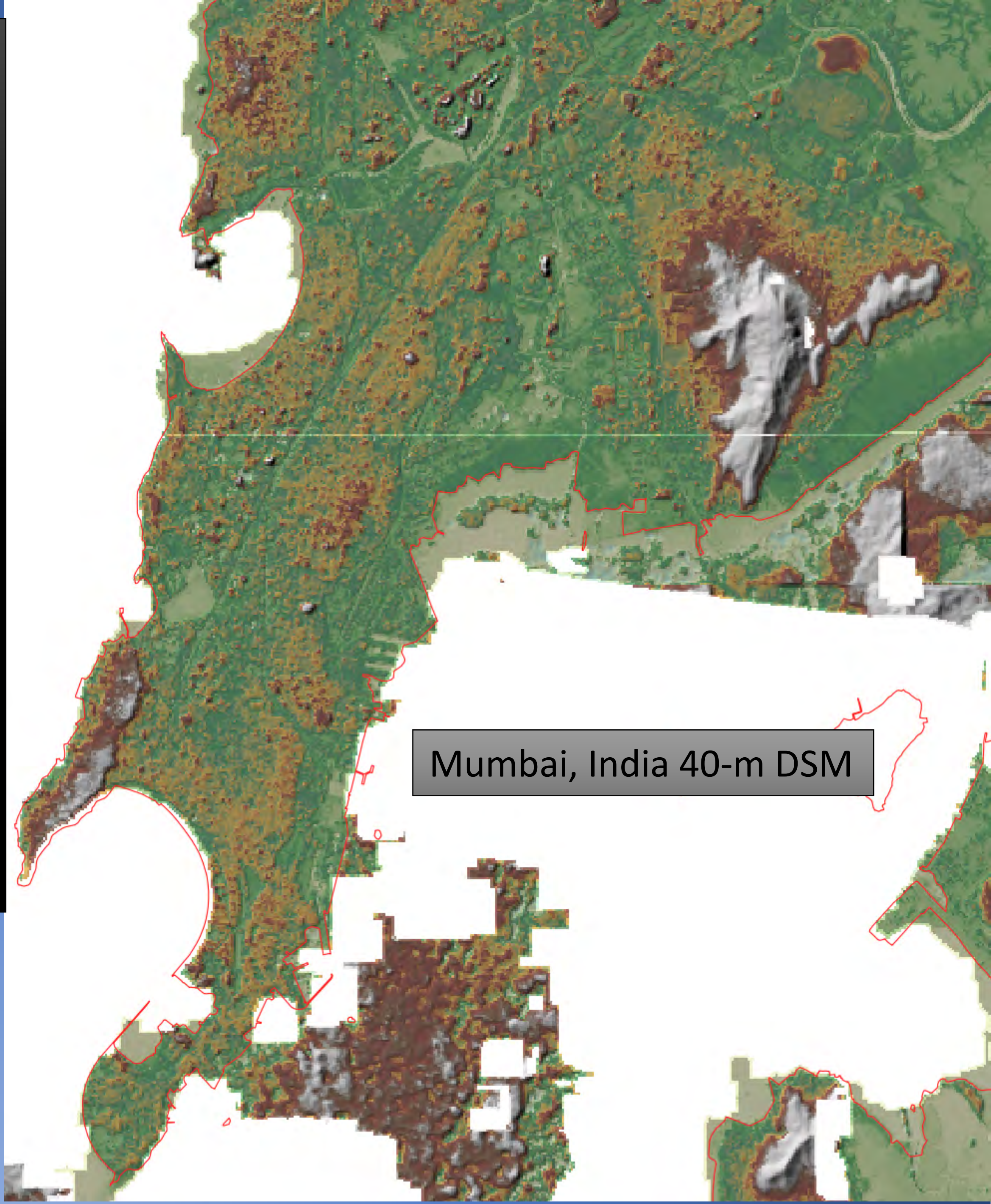
Previous models using SRTM under-predict Risk

Using machine learning with DSMs, Imagery, Synthetic Aperture Radar and Spaceborne Lidar to assess infrastructure, land changes and evolution at each megacity

False positives from deforestation remain an issue

Absolute uncertainties usually better than 50cm

Can do crude bare earth depending on vegetation



Mumbai, India 40-m DSM

Use Optical Derived DSMs, InSAR, GNSS, Global Mean Sea Level Observations, Tidal Observations and Storm models to predict inundation

Previous models using SRTM under-predict Risk

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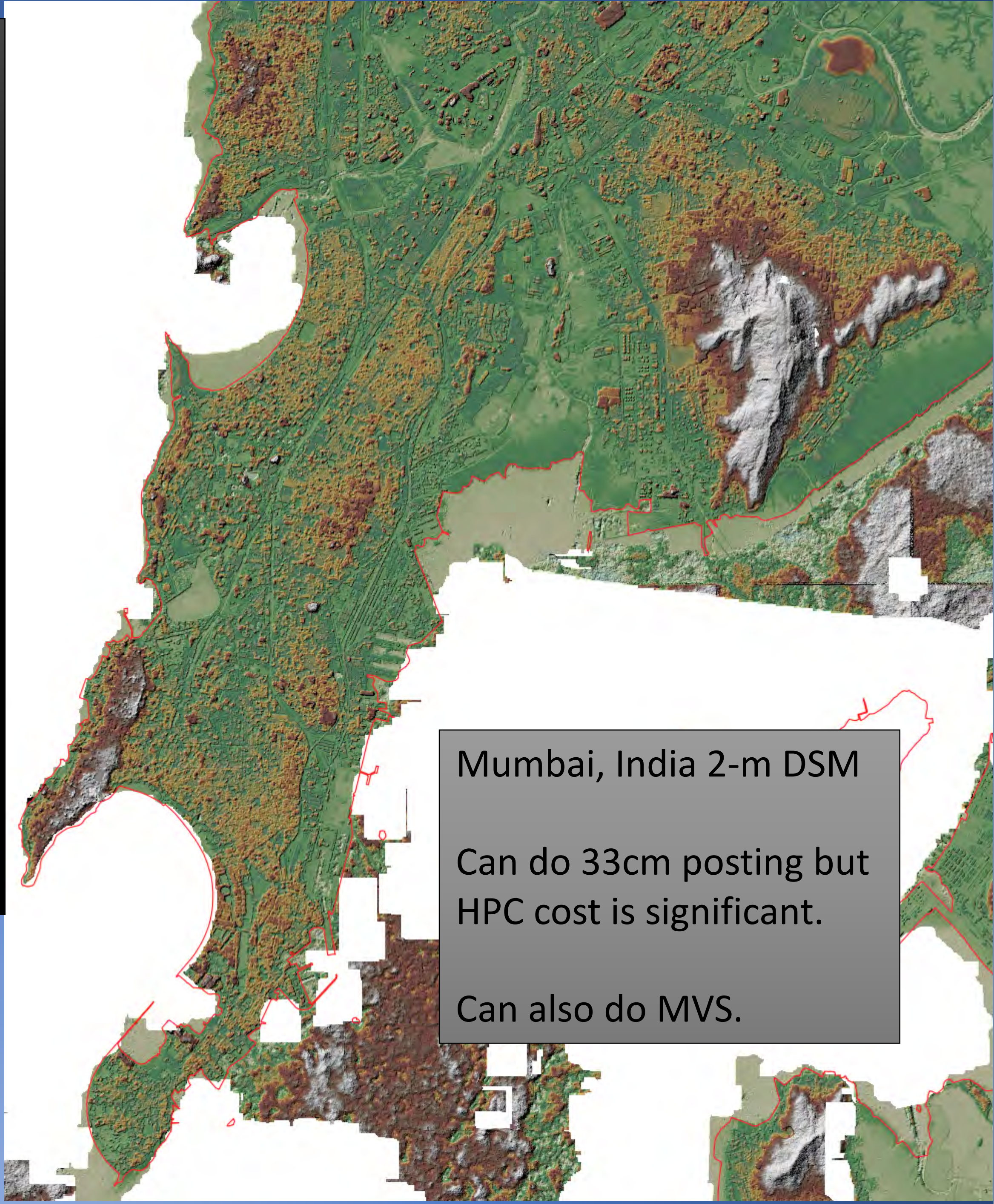

Mumbai, India 2-m DSM

Can do 33cm posting but HPC cost is significant.

Can also do MVS.

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Correcting DSMs with ICESat-2 and GEDI

Filter out ICESat cloudy returns, returns over water.

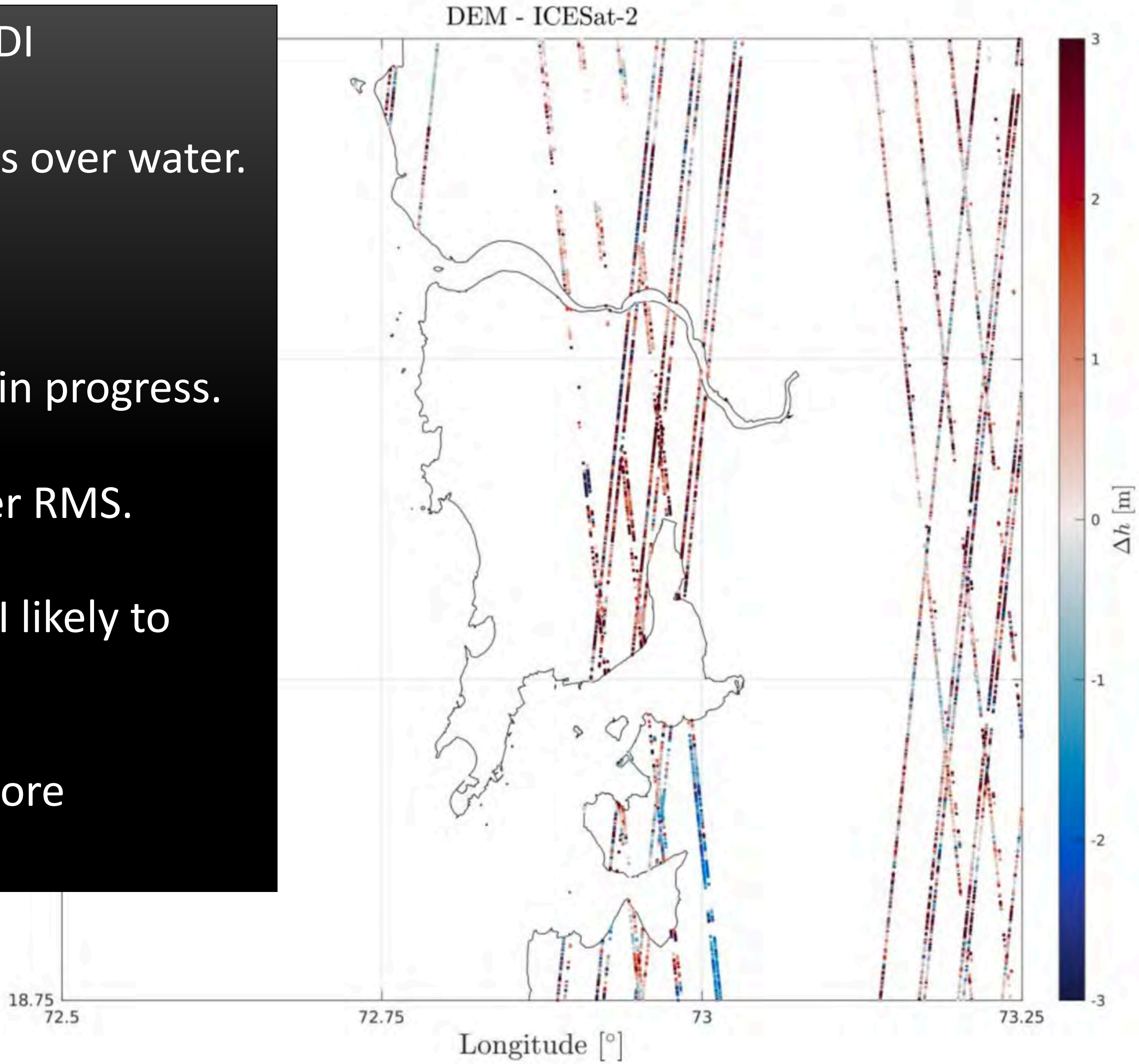
Filtering out returns over vegetation.

Examining effects of different filters is in progress.

Better filters seem provide much better RMS.

More coverage from ICESat-2 and GEDI likely to improve results.

Also using ICESat-2 to examine near shore bathymetry and mean sea level.



Mumbai, Preliminary Sea Level Rise Inundation Result

Mean Sea Level from DTU18 + Perigean tide heights
from FES2014 (2.36 m)
+ inundation height

Full Resolution Bathtub Ring Inundation

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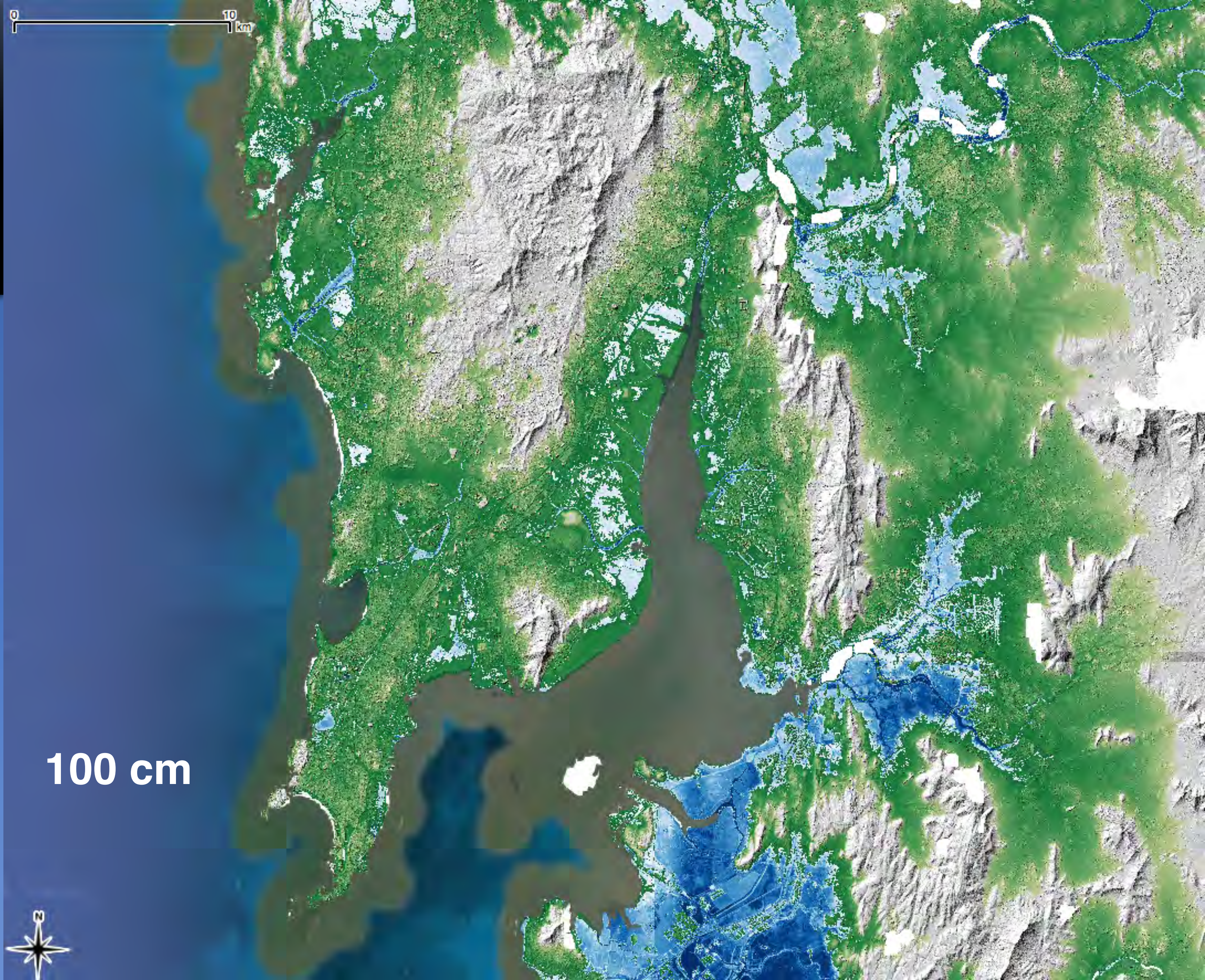


Mumbai, Preliminary Sea Level Rise Inundation Result

DInSAR time series. 800 pairs from 2017 to 2020.

“Vertical” motion
centimeters/yr

- Used Sentinel, Multidimensional small baseline subset (MSBAS) method – SAR improved with DSMs.
- Will use NISAR when available.
- Set basalt outcrop to zero motion.

- Subsidence legacy of building on fill?

Mumbai, Preliminary Sea Level Rise Inundation Result

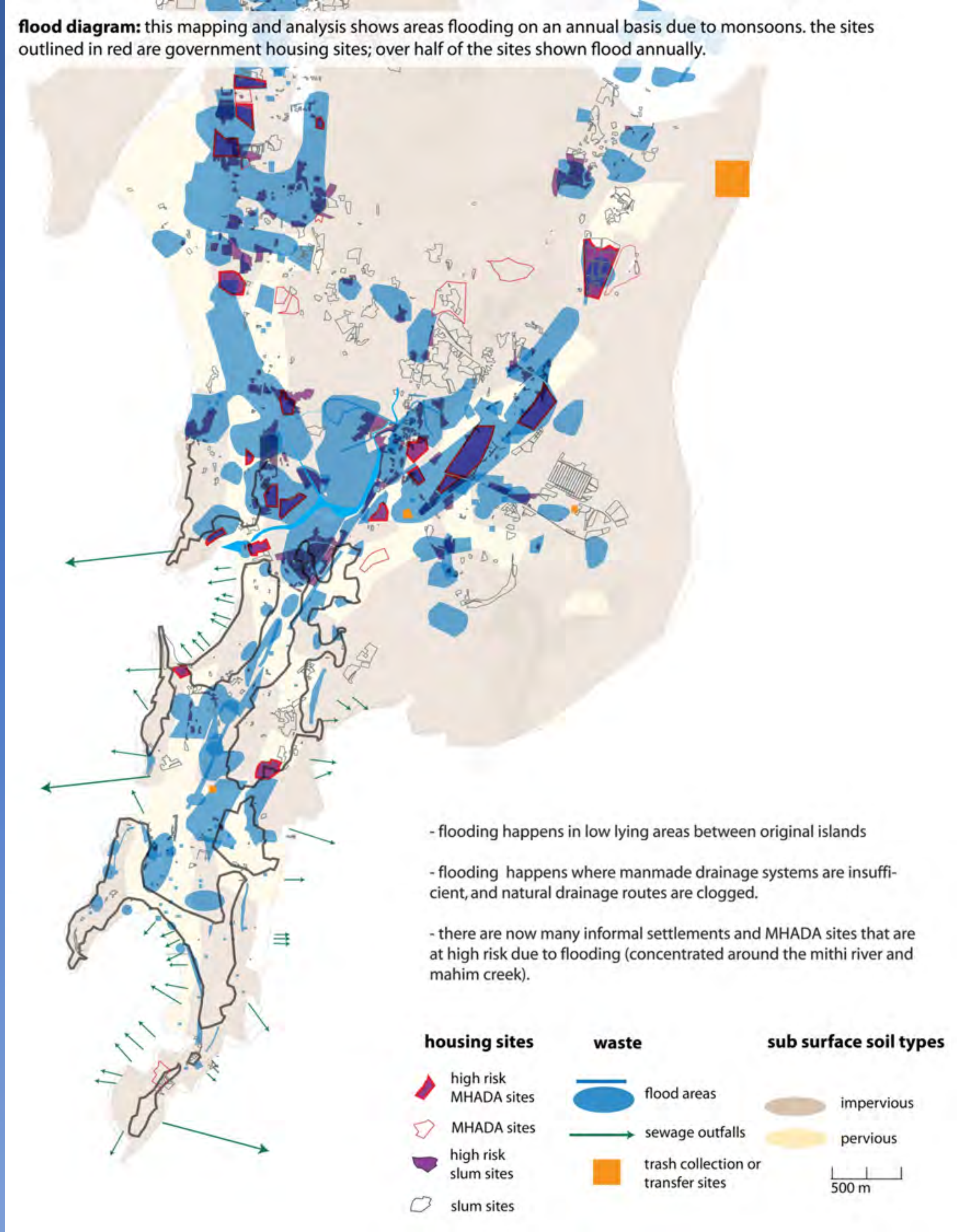
“Vertical” motion centimeters/yr

- DInSAR time series indicates Mumbai rapidly tilting towards the south.
- Need for absolute motions to constrain DInSAR remains.
- No available GNSS rates.

Mumbai, Preliminary Sea Level Rise Inundation Result

Subsidence legacy of building on fill?

Annual monsoon flooding suggests similar story.



flood diagram: this mapping and analysis shows areas flooding on an annual basis due to monsoons. the sites outlined in red are government housing sites; over half of the sites shown flood annually.

- flooding happens in low lying areas between original islands

- flooding happens where manmade drainage systems are insufficient, and natural drainage routes are clogged.

- there are now many informal settlements and MHADA sites that are at high risk due to flooding (concentrated around the mithi river and mahim creek).

Robyn Perkins, Harvard 2008. ASLA

Progress on Cities

Yellow - Done
Cyan - Doing

DigitalGlobe/Maxar acquisitions

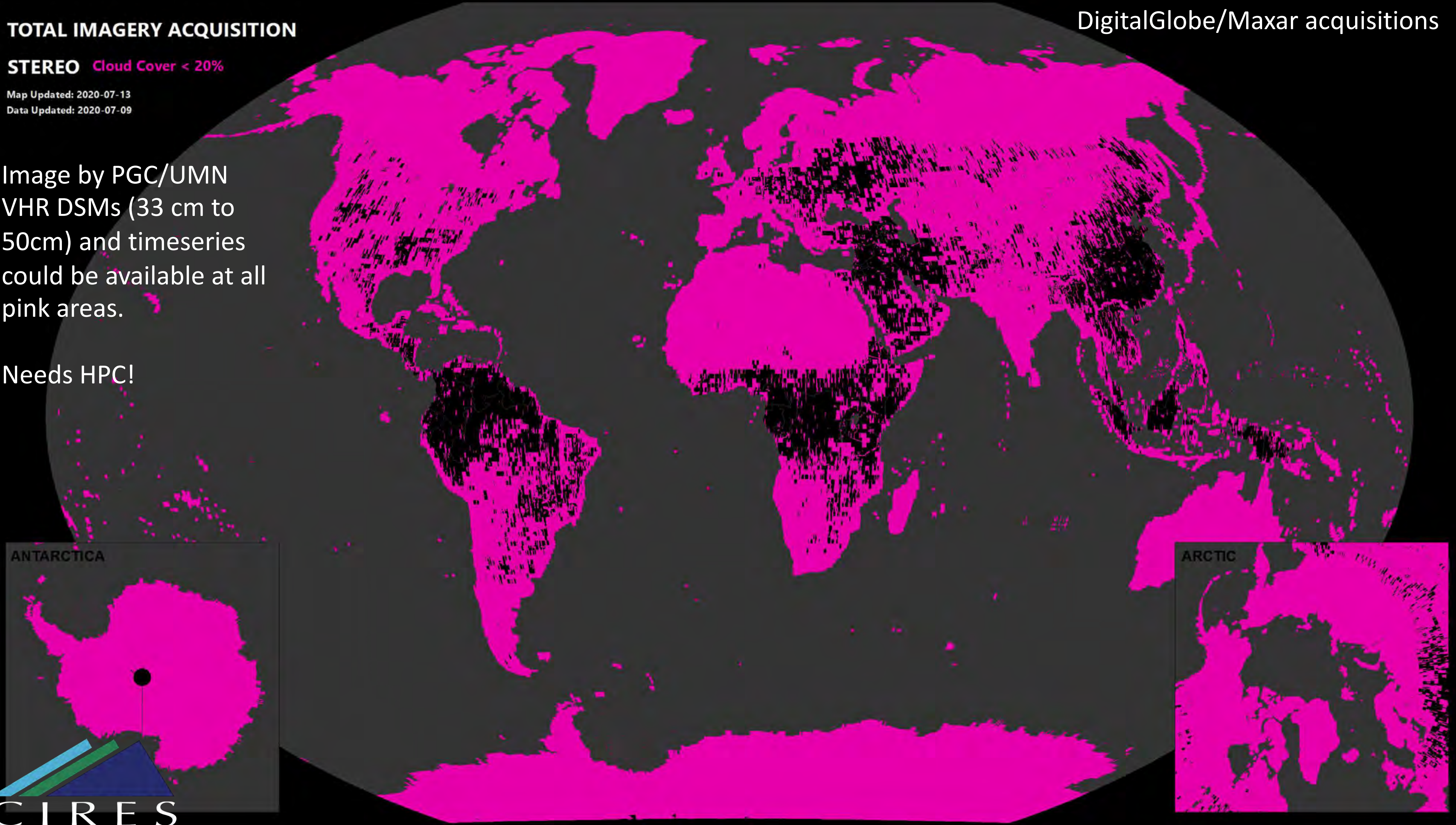


Image by PGC/UMN VHR DSMs (33 cm to 50cm) and timeseries could be available at all pink areas.

Needs HPC!

Conclusions

Coastal cities have an inundation threat.

- Improved, well registered DEMs are necessary
  - Improved near shore mean sea level heights are needed
  - Vertical Land Motions are **critical**
  - Uncertainties need well constrained

  - Our group is using the data for hazards, cryosphere, LULUC studies etc.

Work Supported By NASA Award: 80NSSC17K0565 NASA Sea Level Team
All software used in production is open source and freely available.
Thanks to Geoff Blewitt and Bill Hammond for global VLM files.
This work utilized resources from the University of Colorado Boulder Research Computing Group, which is supported by the National Science Foundation (awards ACI-1532235 and ACI-1532236), the University of Colorado Boulder, and Colorado State University.

CIRES

Solid Earth Applications

Summary

Cathleen Jones

JPL

Objectives: Volcano Hazard Applications

Decadal Survey Science Goal and Objective

(S-1) How can large-scale geological hazards be accurately forecast in a socially relevant timeframe?

(S-1a) Measure the pre-, syn- and post-eruption surface deformation and products of the Earth's entire active land volcano inventory at a time scale of days-weeks.

Volcano Hazards

1. Monitor surface topography at active & quiescent active volcanoes.
2. Map localized topography change associated with volcanic flows to understand physical properties of volcanic flows.

Volcano Disaster Response

1. Monitor volcanic lava-dome growth/collapse
2. Map the extent of eruptive products (lava, lahars, landslides, and pyroclastic flows and ash deposits) from topography change during an eruption.
3. Measure the amount of eruption material and erupted volume as a function of time during an eruption.

Objectives: Earthquake Hazard Applications

Decadal Survey Science Question / Goal

(S-1) How can large-scale geological hazards be accurately forecast in a socially relevant timeframe?

(S-1b) Measure and forecast interseismic, preseismic, coseismic and post-seismic activity over tectonically active areas on time scales ranging from hours to decades.

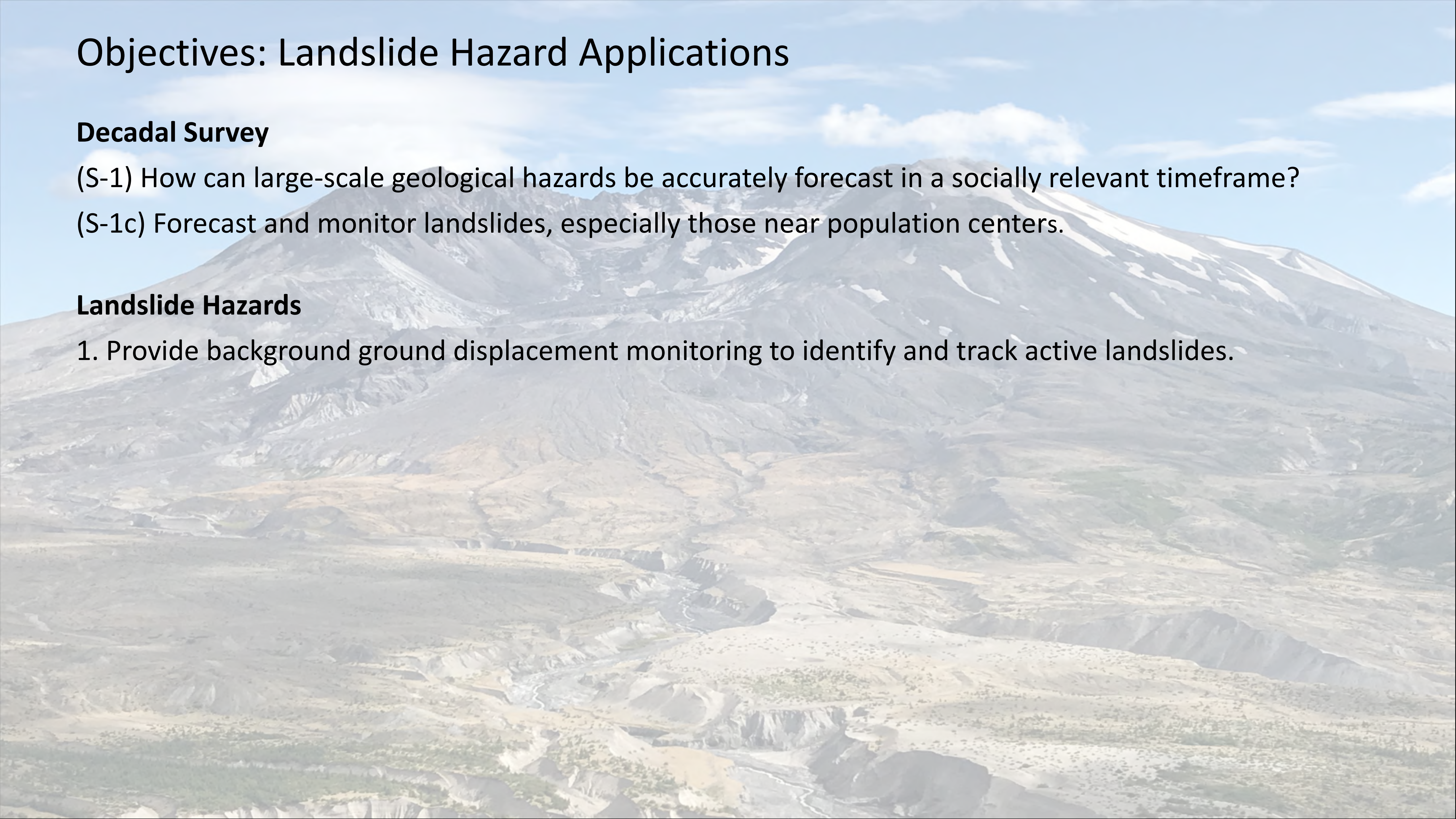
Earthquake Hazards

1. Where is aseismic creep resulting in ground movement occurring and at what rate?
2. Predict earthquakes and assess earthquake risk based on interseismic strain accumulation.
3. Where are faults located, how are faults interconnected, and what is the predicted maximum magnitude and frequency of earthquakes on the fault?
4. **ADD INDUCED SEISMICITY**

Earthquake Disaster Response

1. Where has fault rupture occurred?
2. How much ground movement occurred?
3. Provide model predictions for aftershock location and magnitude.

Objectives: Landslide Hazard Applications



Decadal Survey

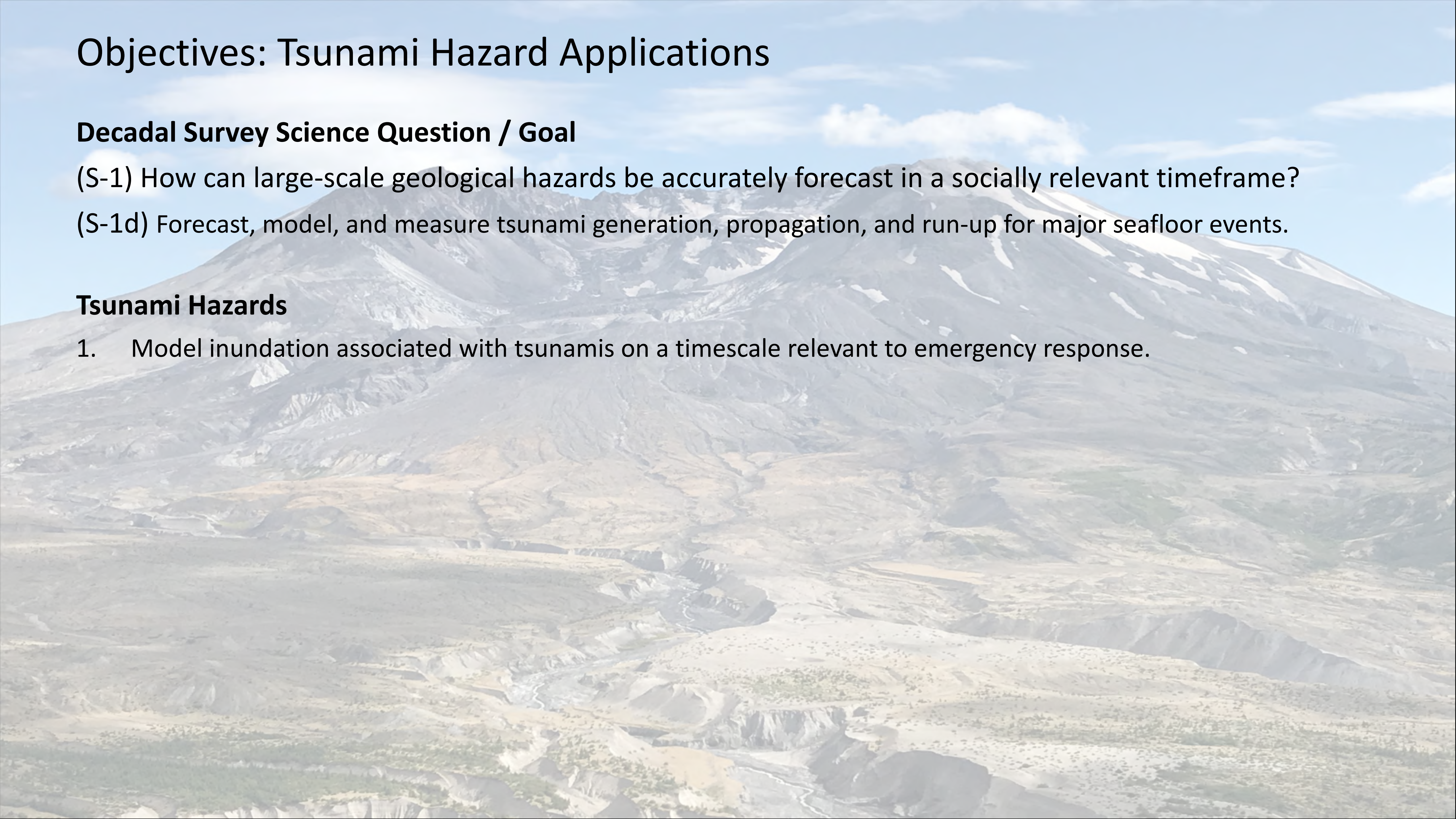
(S-1) How can large-scale geological hazards be accurately forecast in a socially relevant timeframe?

(S-1c) Forecast and monitor landslides, especially those near population centers.

Landslide Hazards

1. Provide background ground displacement monitoring to identify and track active landslides.

Objectives: Tsunami Hazard Applications



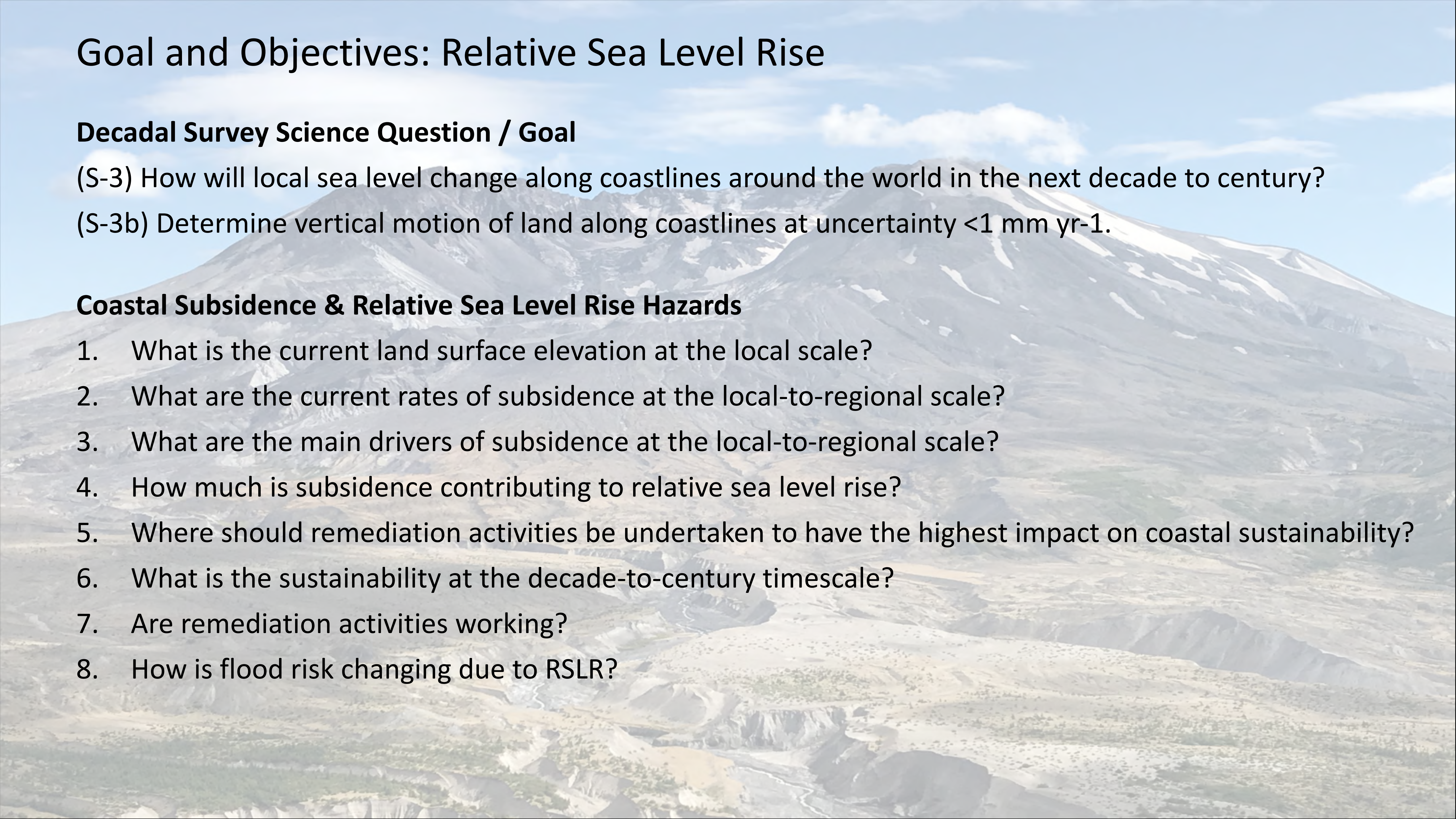
Decadal Survey Science Question / Goal

(S-1) How can large-scale geological hazards be accurately forecast in a socially relevant timeframe?

(S-1d) Forecast, model, and measure tsunami generation, propagation, and run-up for major seafloor events.

Tsunami Hazards

1. Model inundation associated with tsunamis on a timescale relevant to emergency response.



Goal and Objectives: Relative Sea Level Rise

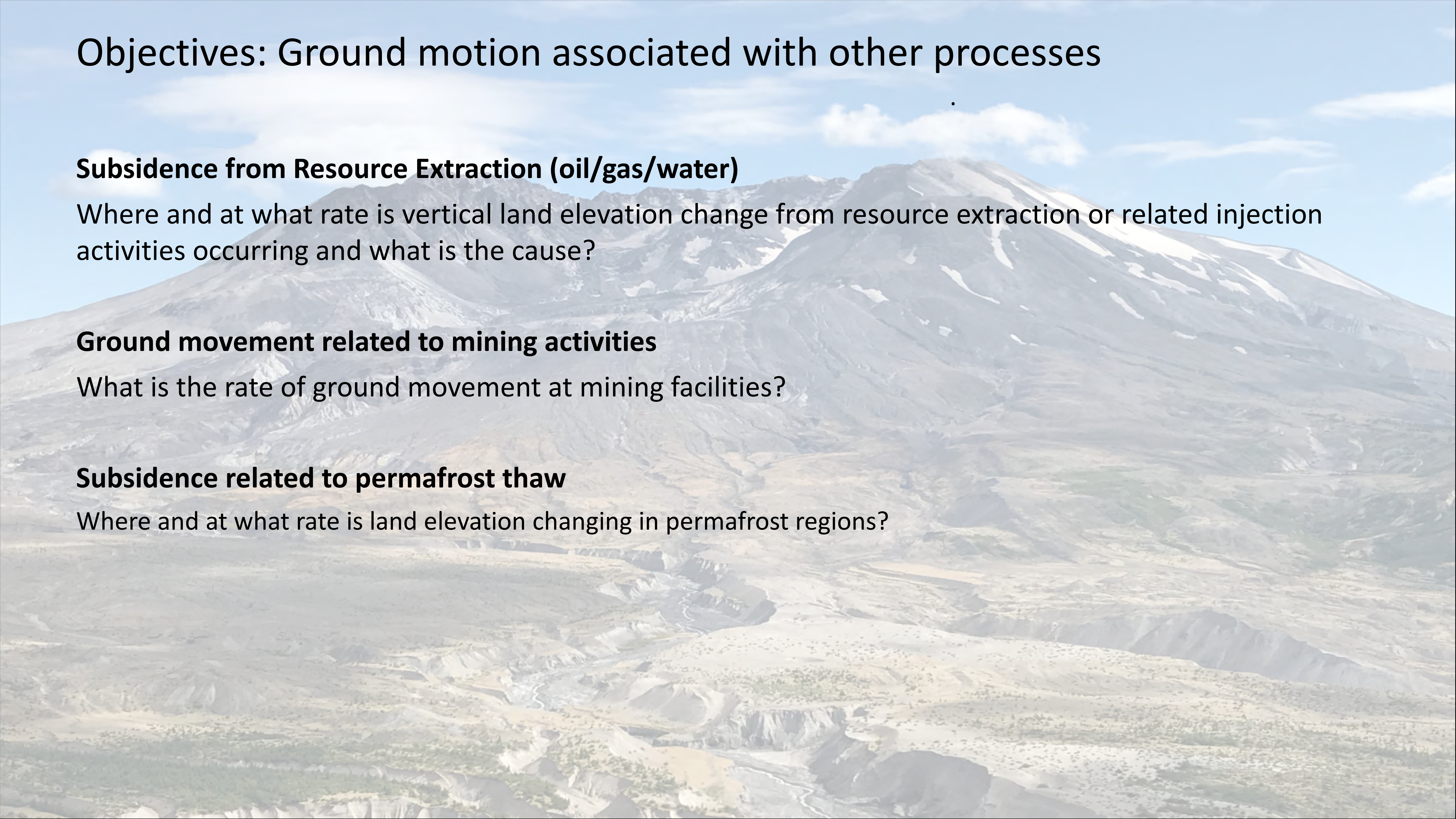
Decadal Survey Science Question / Goal

(S-3) How will local sea level change along coastlines around the world in the next decade to century?

(S-3b) Determine vertical motion of land along coastlines at uncertainty <1 mm yr-1.

Coastal Subsidence & Relative Sea Level Rise Hazards

1. What is the current land surface elevation at the local scale?
2. What are the current rates of subsidence at the local-to-regional scale?
3. What are the main drivers of subsidence at the local-to-regional scale?
4. How much is subsidence contributing to relative sea level rise?
5. Where should remediation activities be undertaken to have the highest impact on coastal sustainability?
6. What is the sustainability at the decade-to-century timescale?
7. Are remediation activities working?
8. How is flood risk changing due to RSLR?



Objectives: Ground motion associated with other processes

Subsidence from Resource Extraction (oil/gas/water)

Where and at what rate is vertical land elevation change from resource extraction or related injection activities occurring and what is the cause?

Ground movement related to mining activities

What is the rate of ground movement at mining facilities?

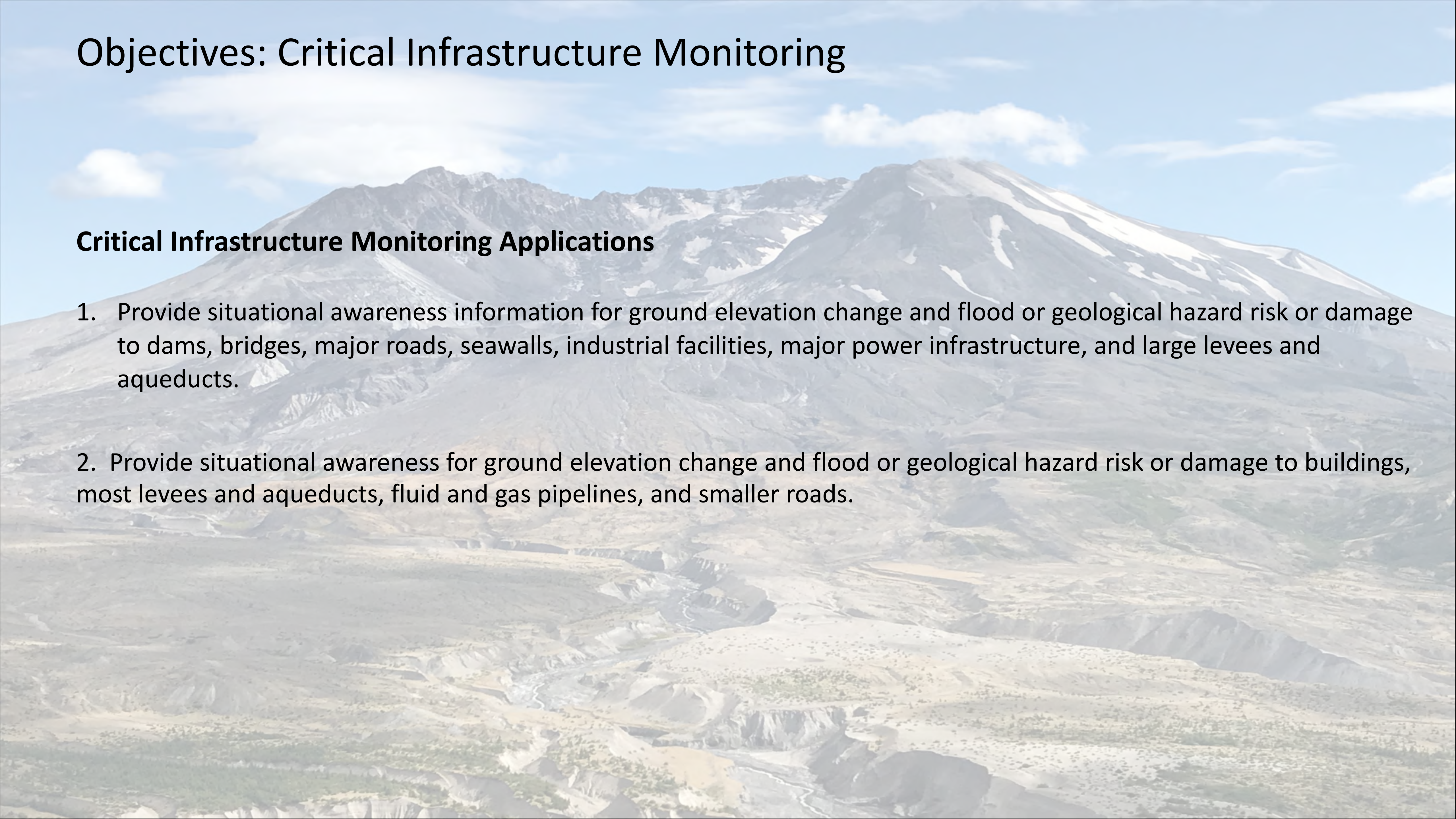
Subsidence related to permafrost thaw

Where and at what rate is land elevation changing in permafrost regions?

Objectives: Sinkhole & Cavern Collapse Applications

Sinkhole & Cavern Collapse Hazards Applications

1. Identify topography change related to sinkhole precursors & progression.
   1.a Where have sinkholes formed in the past?
   1.b Where are sinkholes actively changing the ground surface elevation now?
2. Is the rate of ground movement associated with a sinkhole constant or accelerating (collapse precursor detection)?
3. What is the underlying cause (human activity vs. natural), i.e., related to rainfall, groundwater extraction, mining, etc.?



Objectives: Critical Infrastructure Monitoring

Critical Infrastructure Monitoring Applications

1. Provide situational awareness information for ground elevation change and flood or geological hazard risk or damage to dams, bridges, major roads, seawalls, industrial facilities, major power infrastructure, and large levees and aqueducts.

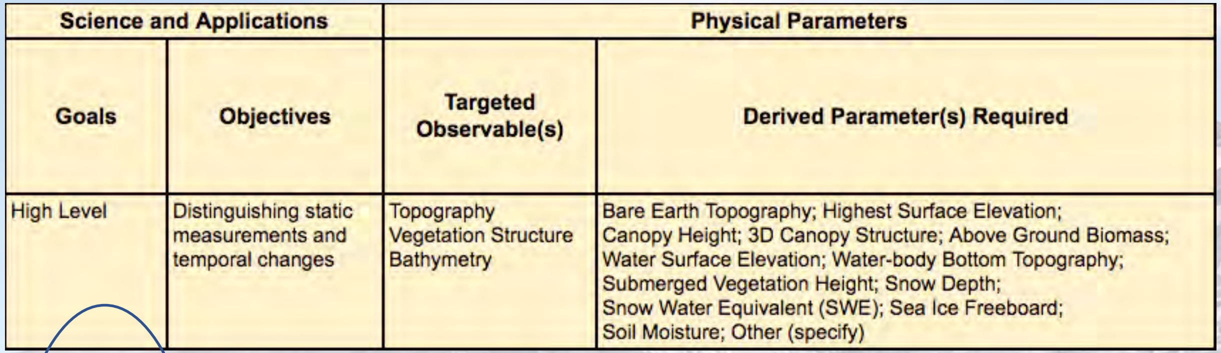
2. Provide situational awareness for ground elevation change and flood or geological hazard risk or damage to buildings, most levees and aqueducts, fluid and gas pipelines, and smaller roads.

Objectives: Space Archaeology

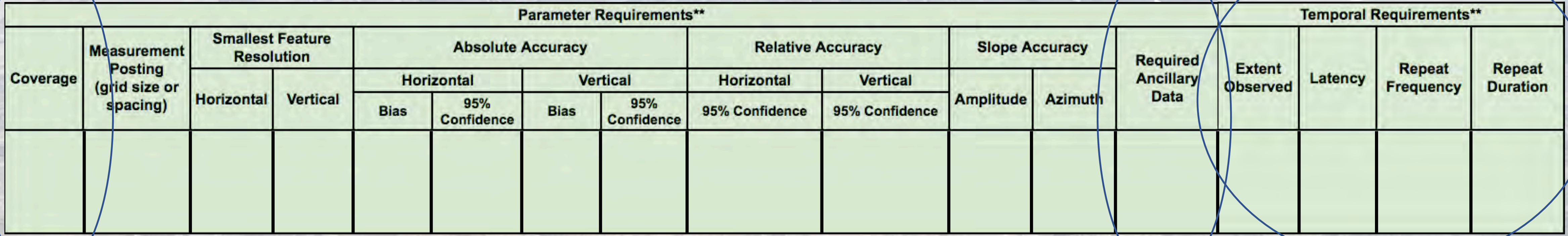
Space Archaeology

1. Identify and map archaeological heritage sites in remote locations.

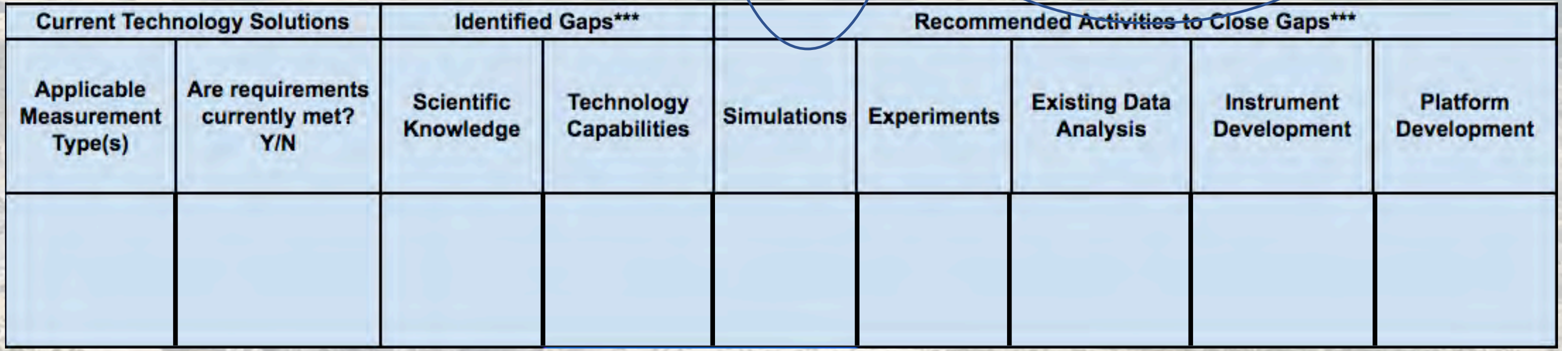
SATM Structure



Science and Applications		Physical Parameters	
Goals	**Objectives**	**Targeted Observable(s)**	**Derived Parameter(s) Required**
High Level	Distinguishing static measurements and temporal changes	Topography Vegetation Structure Bathymetry	Bare Earth Topography; Highest Surface Elevation; Canopy Height; 3D Canopy Structure; Above Ground Biomass; Water Surface Elevation; Water-body Bottom Topography; Submerged Vegetation Height; Snow Depth; Snow Water Equivalent (SWE); Sea Ice Freeboard; Soil Moisture; Other (specify)



Parameter Requirements**													Temporal Requirements**			
Coverage	**Measurement Posting (grid size or spacing)**	**Smallest Feature Resolution**		**Absolute Accuracy**				**Relative Accuracy**		**Slope Accuracy**		**Required Ancillary Data**	**Extent Observed**	**Latency**	**Repeat Frequency**	**Repeat Duration**
		Horizontal	**Vertical**	**Horizontal**		**Vertical**		**Horizontal**	**Vertical**	**Amplitude**	**Azimuth**					
				Bias	**95% Confidence**	**Bias**	**95% Confidence**	**95% Confidence**	**95% Confidence**							



Current Technology Solutions		Identified Gaps***		Recommended Activities to Close Gaps***				
Applicable Measurement Type(s)	**Are requirements currently met? Y/N**	**Scientific Knowledge**	**Technology Capabilities**	**Simulations**	**Experiments**	**Existing Data Analysis**	**Instrument Development**	**Platform Development**