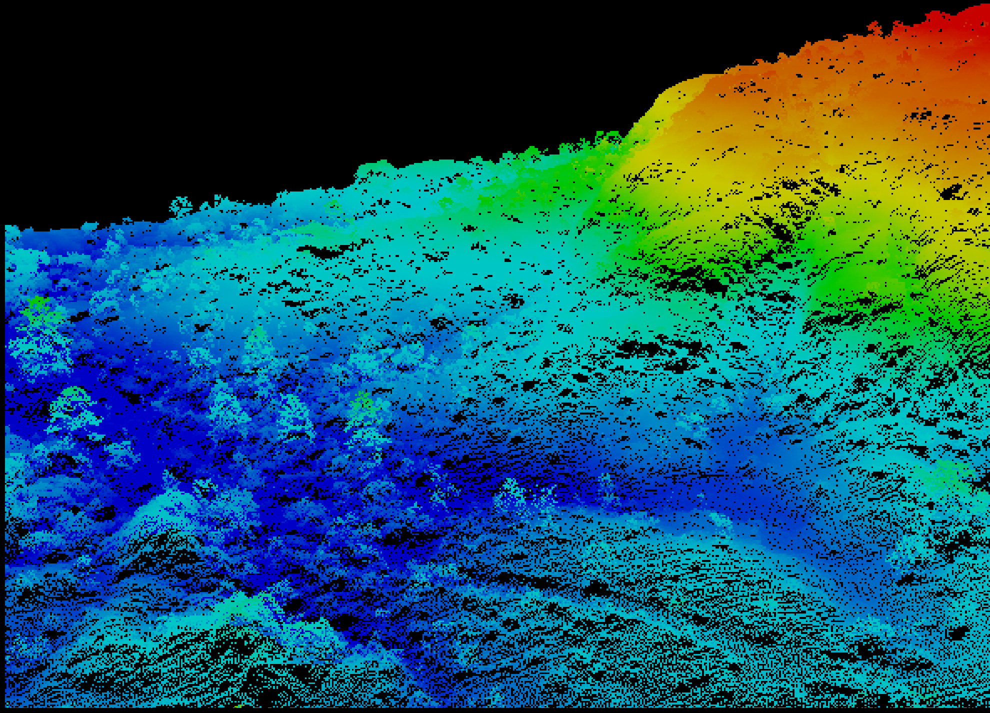
Sharpening our view of earth processes with high resolution topography

Denali 2002 earthquake rupture (EarthScope)



Granite Dells AZ point cloud (NCALM student seed grant)

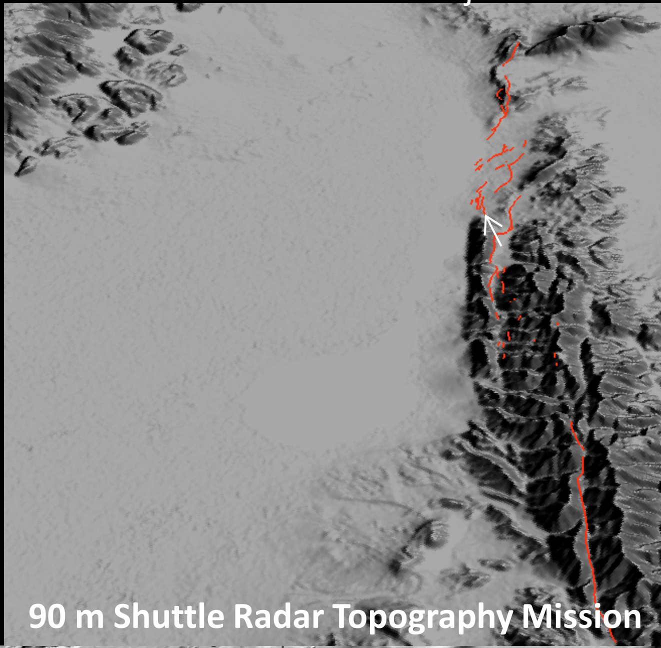
Sharpening our view of earth processes with high resolution topography Introduction and LiDAR

J Ramón Arrowsmith
School of Earth and Space Exploration
Arizona State University

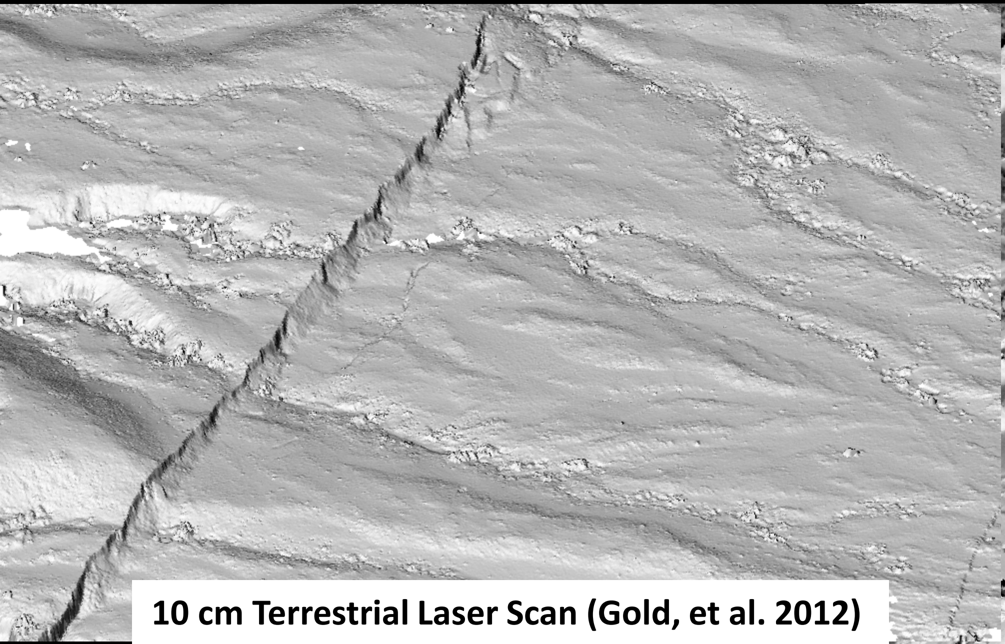
Major contributions from
C. Crosby, G. Hilley, E. Nissen, B. Salisbury, S. Saripalli, O. Zielke

Data and processing: B4, NCALM, OpenTopography
Supported by NSF, USGS, SCEC, NASA

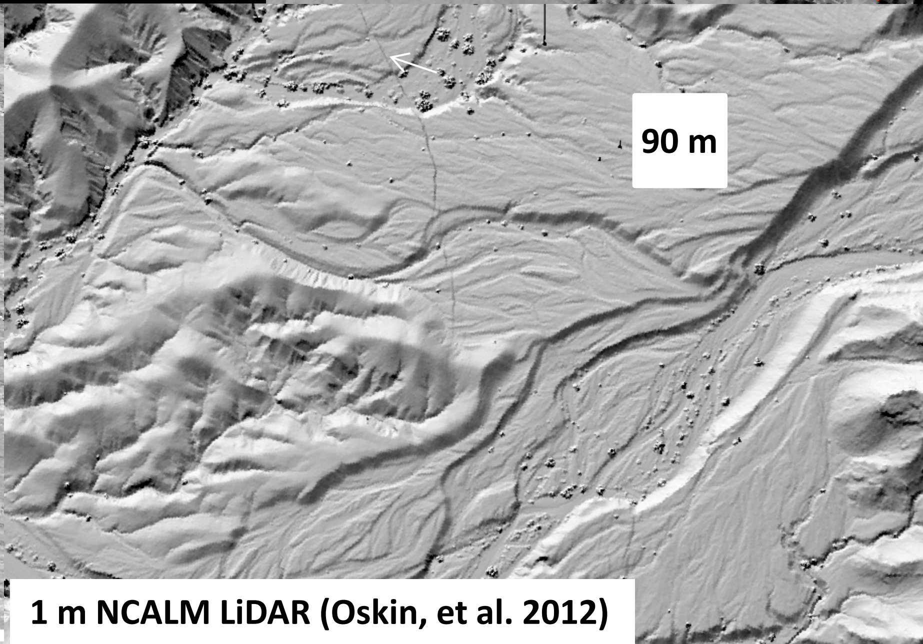
2010 El Mayor Cucupah earthquake, Baja California



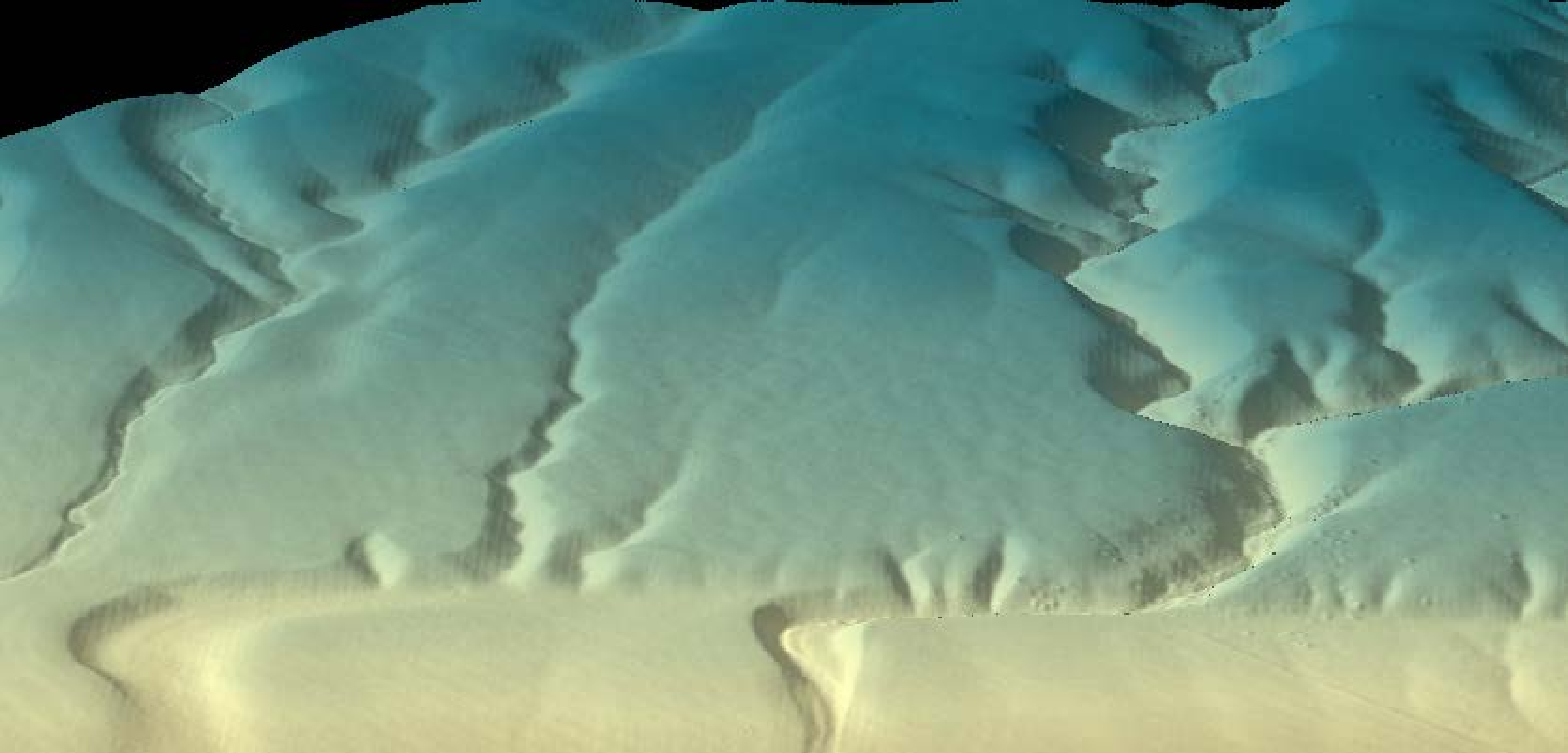
90 m Shuttle Radar Topography Mission



10 cm Terrestrial Laser Scan (Gold, et al. 2012)



1 m NCALM LiDAR (Oskin, et al. 2012)

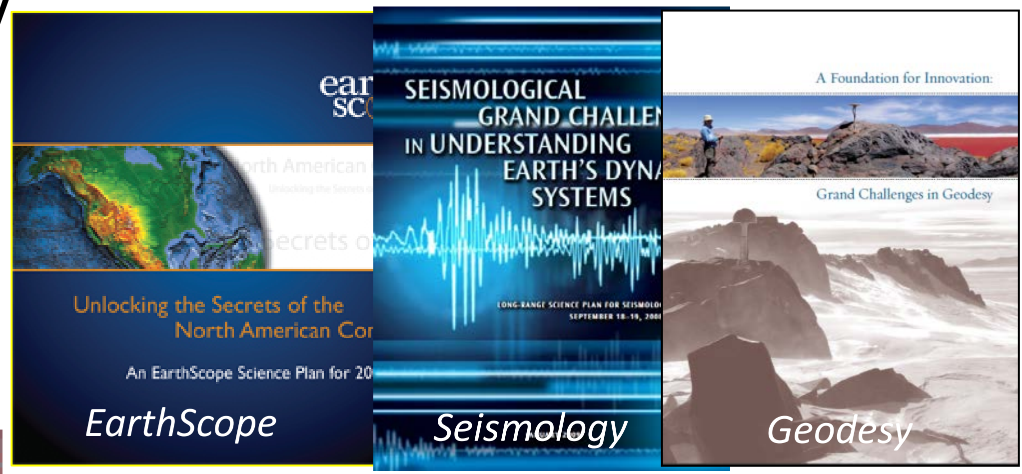


Outline

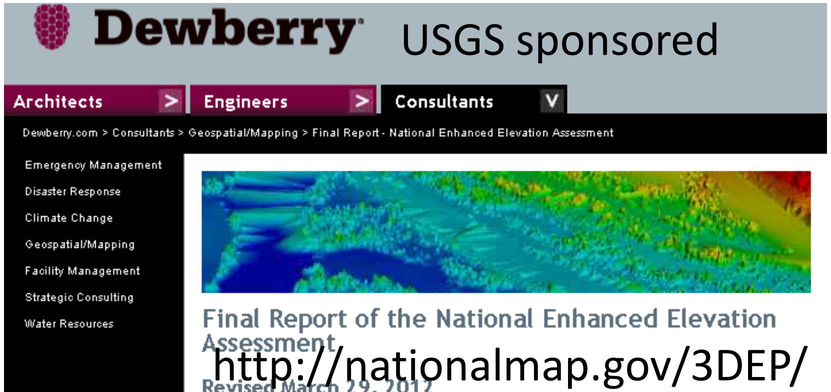
- **Introduction and measuring topography**
- “Seeing” at the appropriate scale
- Fault trace mapping
- Reconstructing slip history
- Understanding geomorphic response to uplift
- 3D topographic differencing

Background: 0.5 m Digital Elevation Model along the south-central San Andreas Fault

Major US community studies recognize the scientific value of high resolution topography



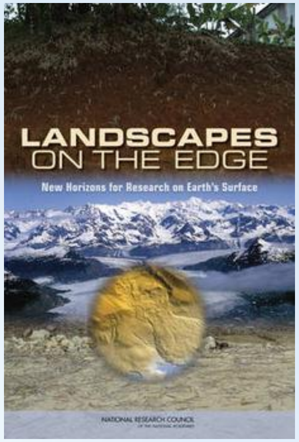
Science communities



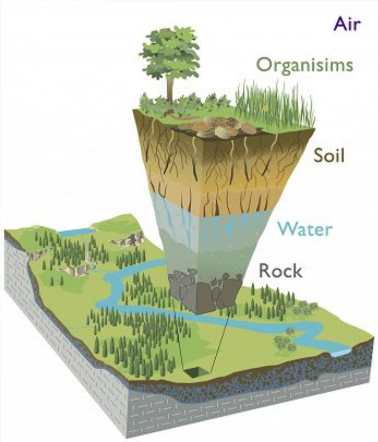
USGS sponsored

http://nationalmap.gov/3DEP/

Example scientific motivations



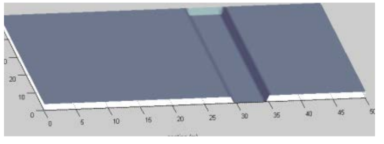
- How do geopatterns on the Earth’s surface arise and what do they tell us about processes?
- How do landscapes influence and record climate and tectonics?
- What are the transport laws that govern the evolution of the Earth’s surface?



- Coupled hydrogeomorphic-ecosystem response to natural and anthropogenic change
- Landscape and ecosystem dynamics
- Scaling, model parameterization, linkages to in situ observations, integration with other remote sensing data (e.g., atmospheric, water, ice)

Landscape development in areas of active deformation

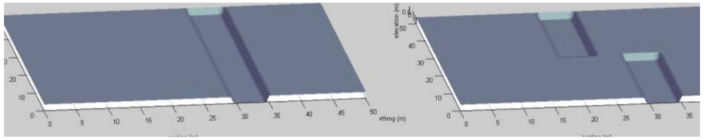
Original elevation



$$H_0(x, y)$$

Landscape development in areas of active deformation

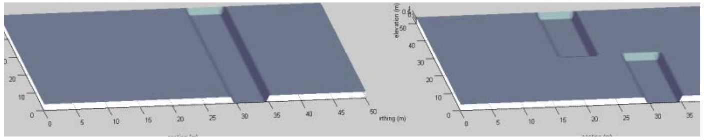
Original elevation + Tectonic displacement



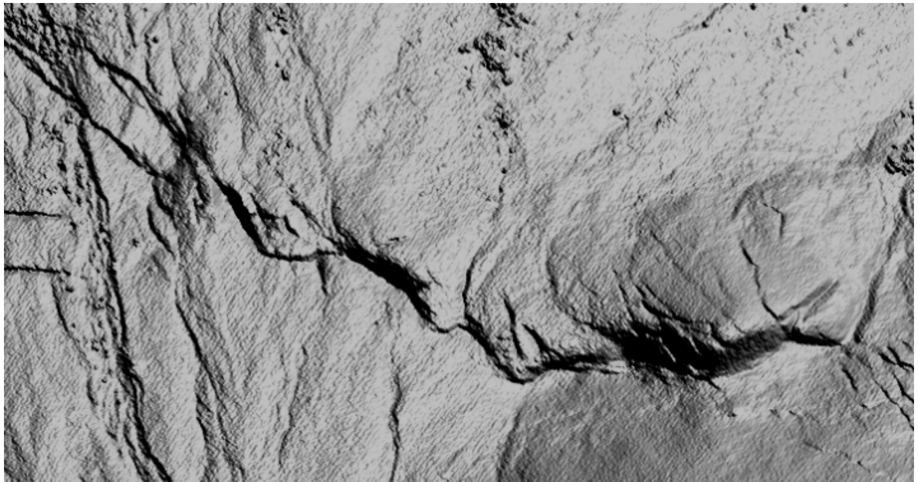
$$H_0(x,y) + U(x,y,t,H)$$

Landscape development in areas of active deformation

Original elevation + Tectonic displacement



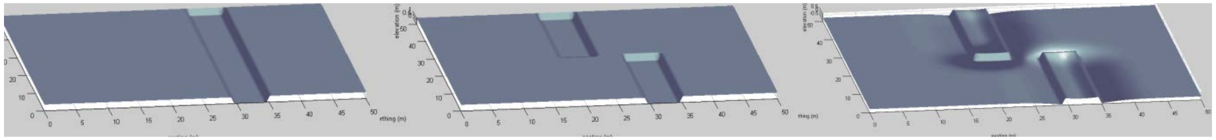
$$H_0(x, y) + U(x, y, t, H)$$



Denali 2002 earthquake rupture
(EarthScope)

Landscape development in areas of active deformation

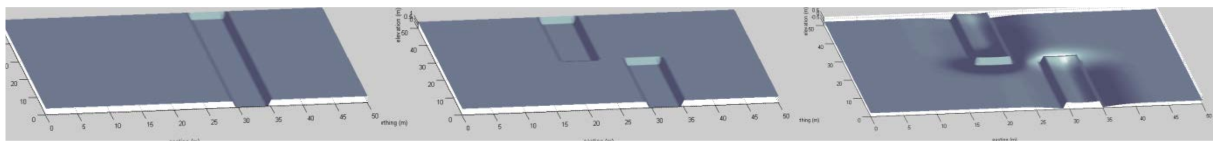
Original elevation + Tectonic displacement + Geomorphic displacement



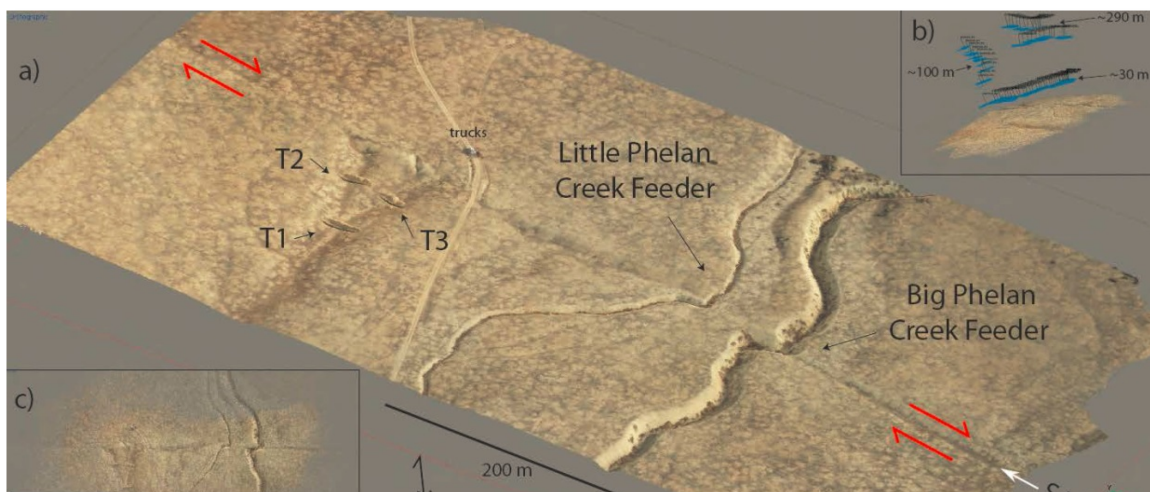
$$H_0(x, y) + U(x, y, t, H) + V(x, y, t, H)$$

Landscape development in areas of active deformation

Original elevation + Tectonic displacement + Geomorphic displacement



$$H_0(x,y) + U(x,y,t,H) + V(x,y,t,H)$$

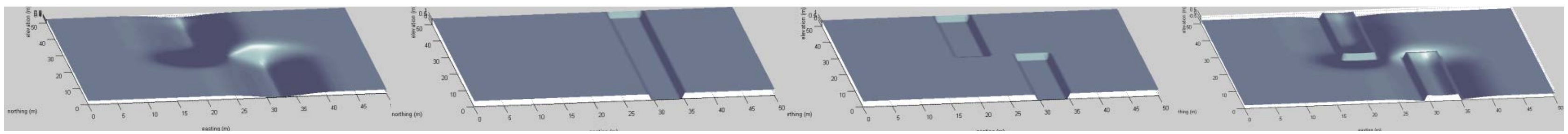


Barrett Salisbury (ASU)

Landscape development in areas of active deformation

Surface processes act to change elevation through erosion and deposition while tectonic processes depress or elevate the surface directly.

Current elevation = Original elevation + Tectonic displacement + Geomorphic displacement



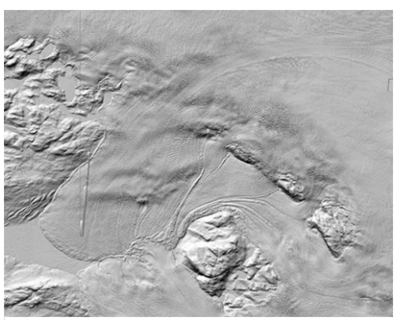
$$H(x,y,t) = H_0(x,y) + U(x,y,t,H) + V(x,y,t,H)$$

Geomorphic markers are landscape elements for whose geomorphic displacements (erosion and sedimentation are small enough or understandable that the tectonic displacement can be interpreted)

Getting the right coverage in time, space, and resolution for the question

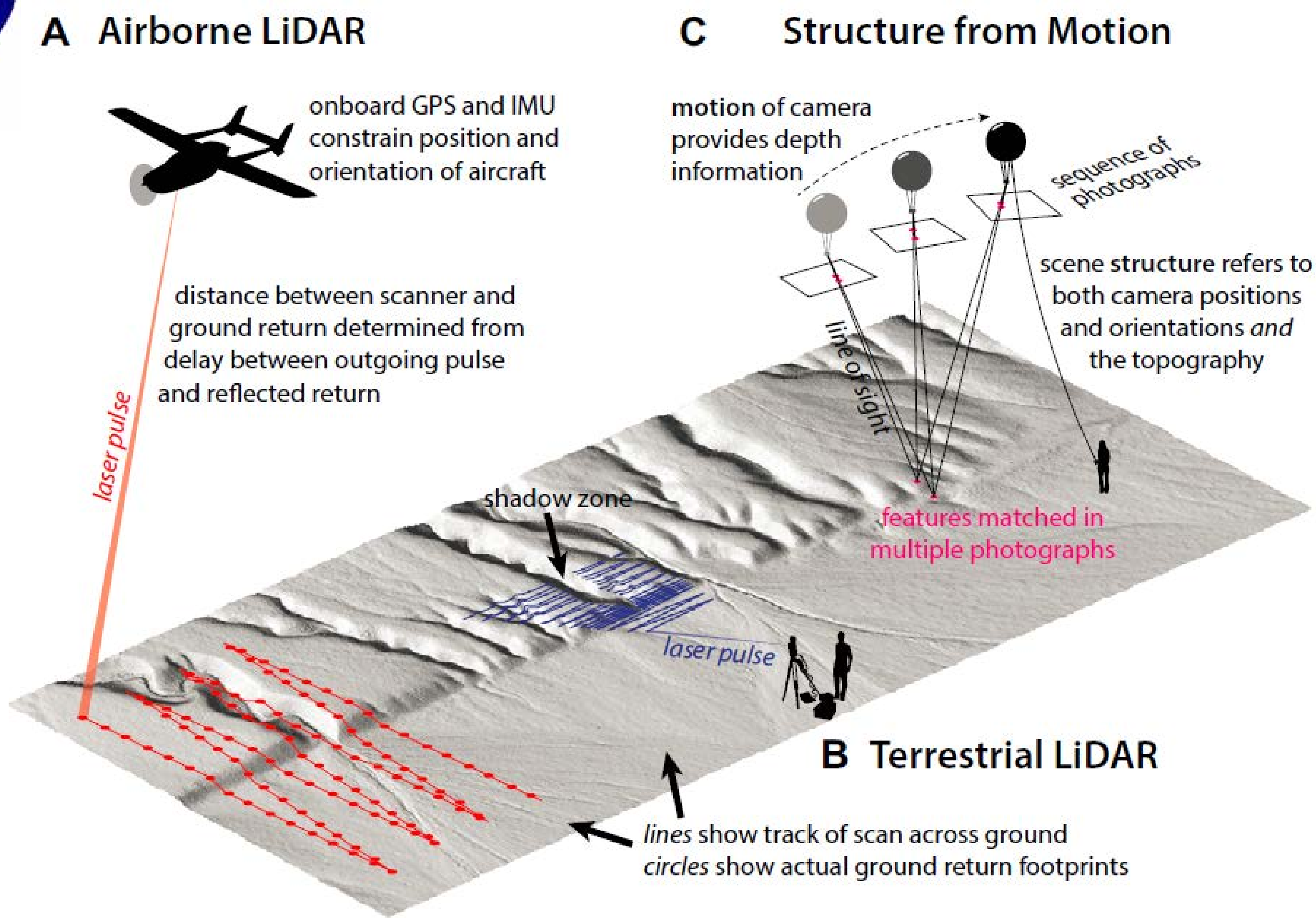
Global and regional topography/bathy (10s-100s m/pix)

+ASTER



Stereo-Photogrammetric Elevation Model (Polar Geospatial Center)

Local to site scale topography (dm to m / pix)



Johnson, K., Nissen, E., Saripalli, S., Arrowsmith, J R., McGarey, P., Scharer, K., Williams, P., Blisniuk, K., Rapid mapping of ultra-fine fault zone topography with Structure from Motion, Geosphere, v. 10; no. 5; p. 1–18; doi:10.1130/GES01017.1, 2014.

Lembang Fault, South of Bandung, Java, Indonesia (6/25/2013)

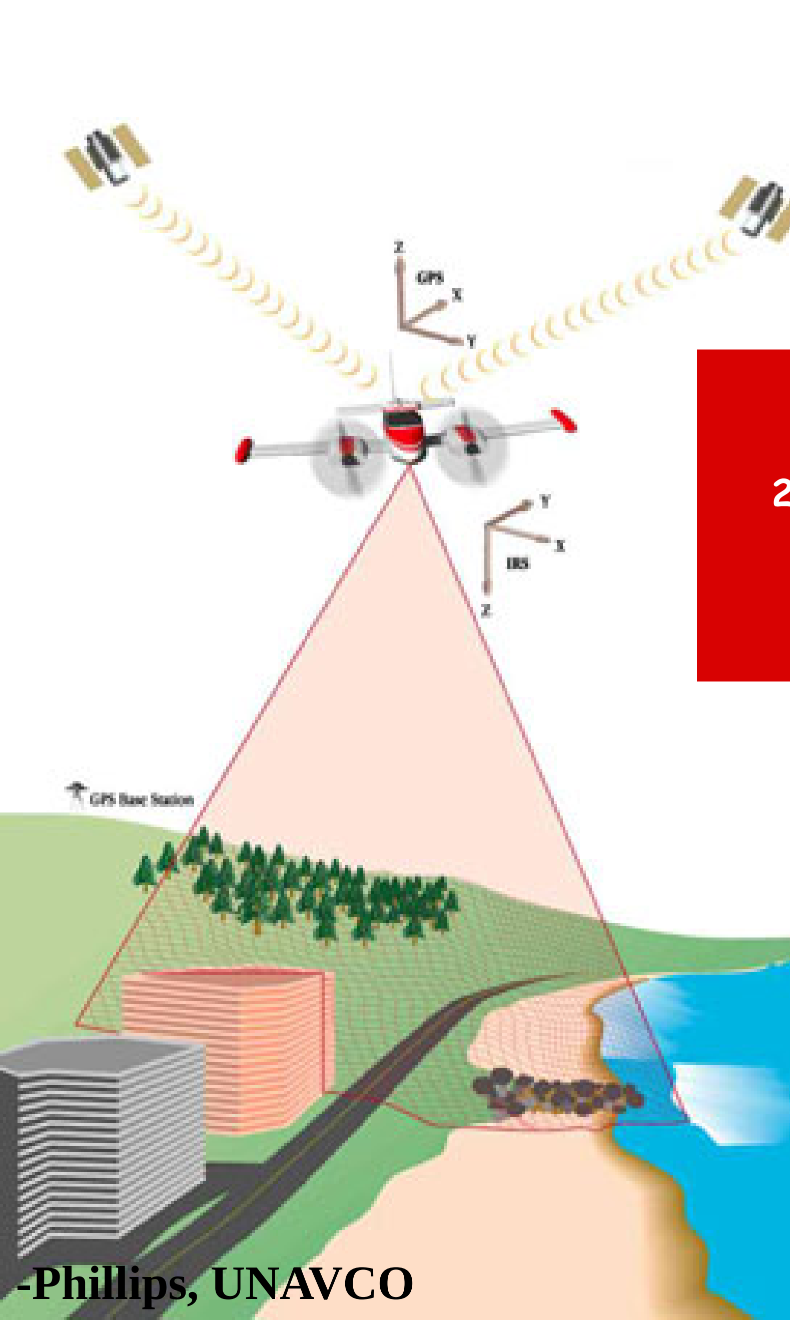
LIPI/ITB short course materials: 30 lectures and 10 exercises

http://activetectonics.la.asu.edu/lipi

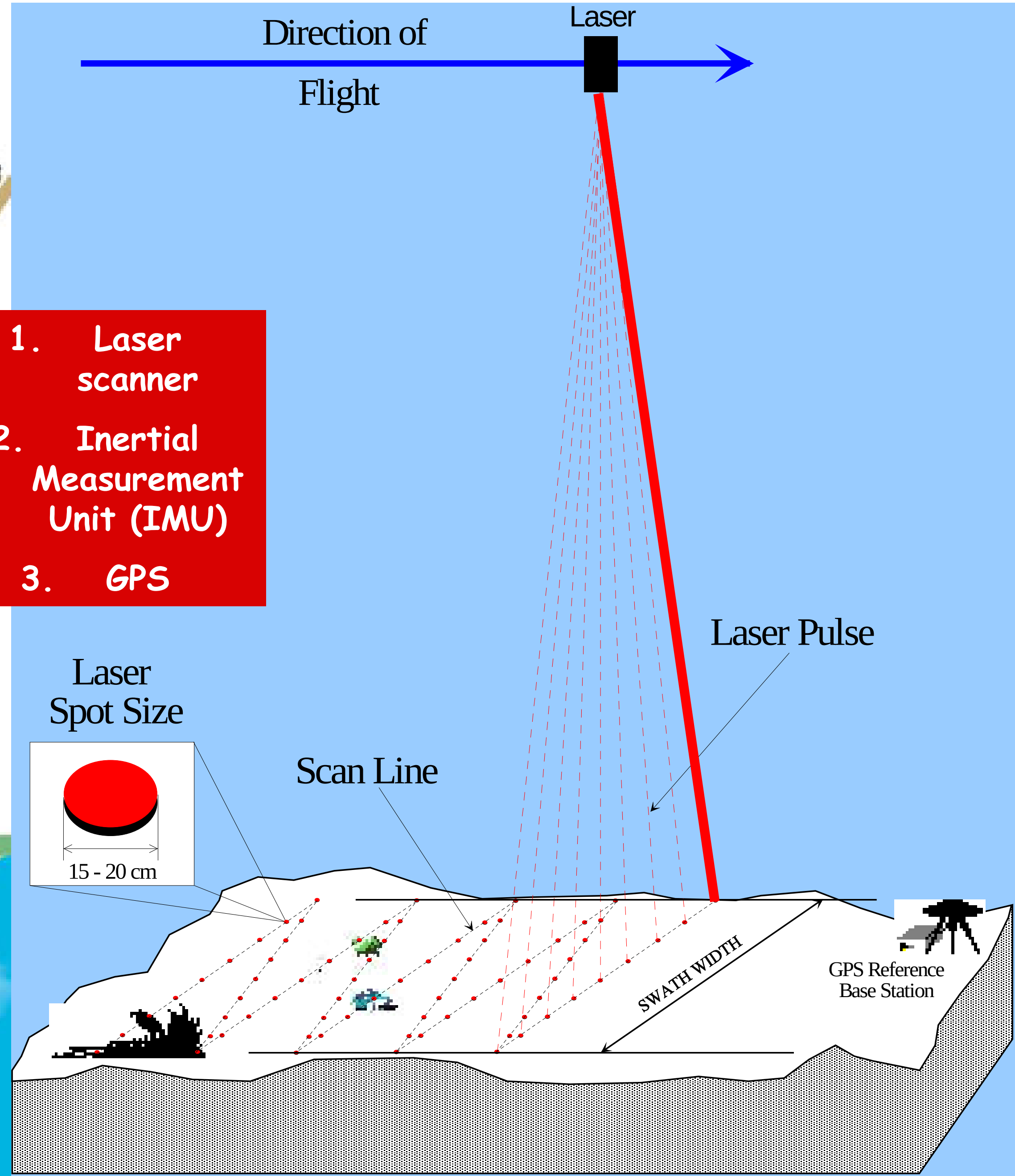


Parongpong Site

Airborne Laser Swath Mapping (ALSM)



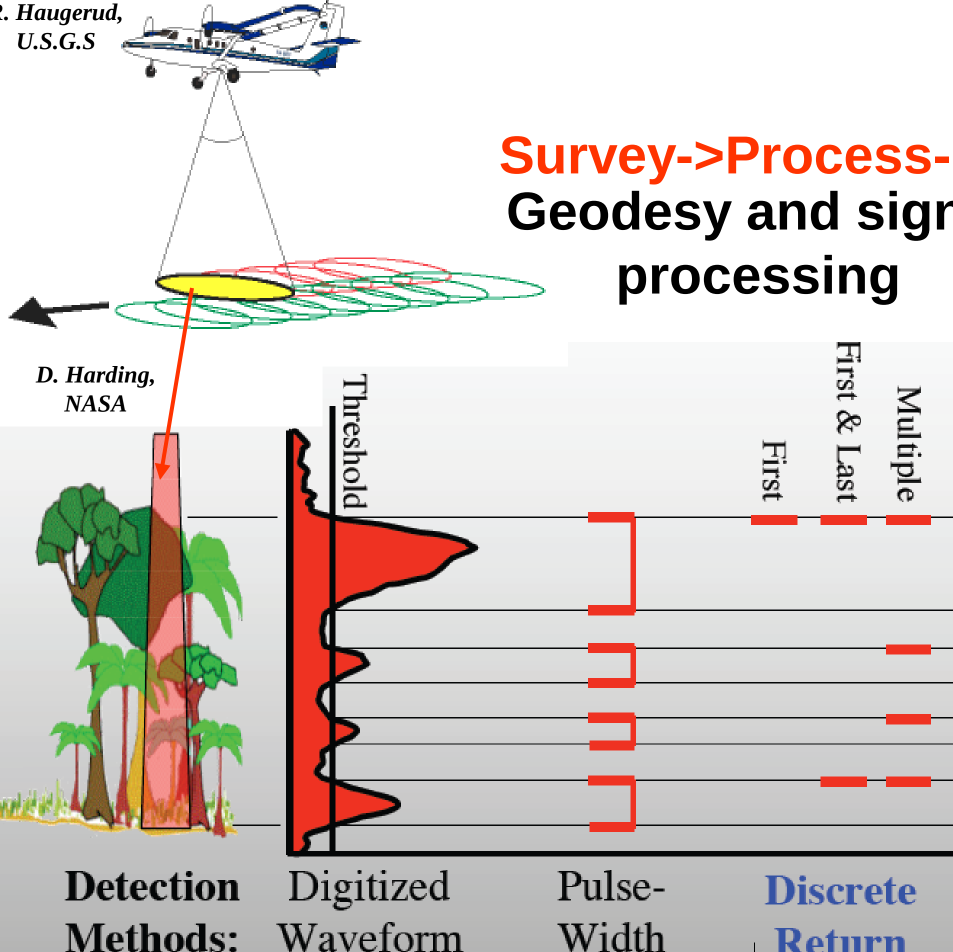
1. Laser scanner
2. Inertial Measurement Unit (IMU)
3. GPS



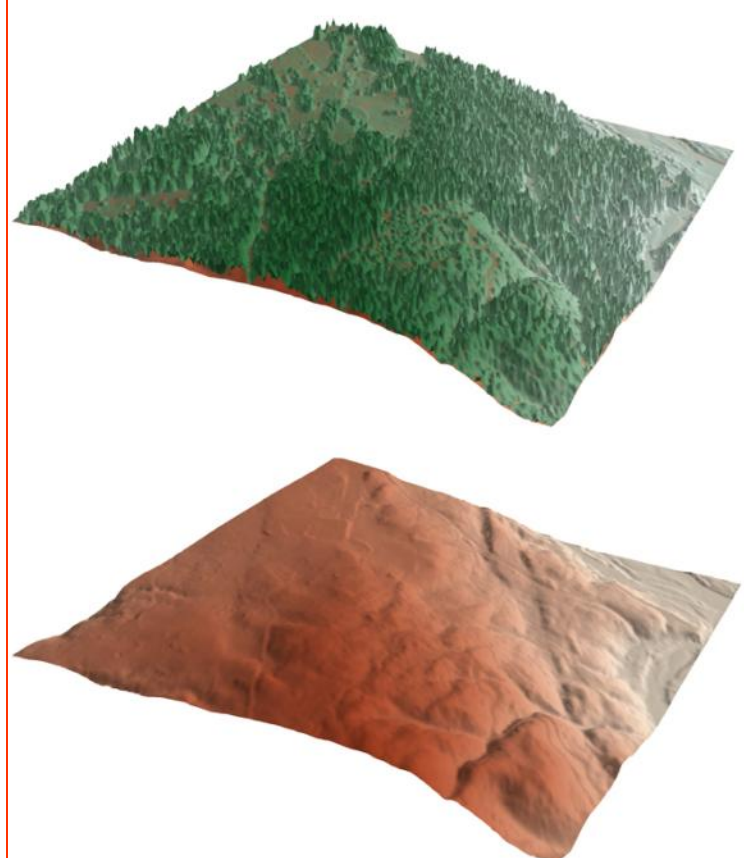
ALSM workflow:

Survey->Process->Classify->Interpolate/Grid->Analyze

Geodesy and signal processing



Gridded products

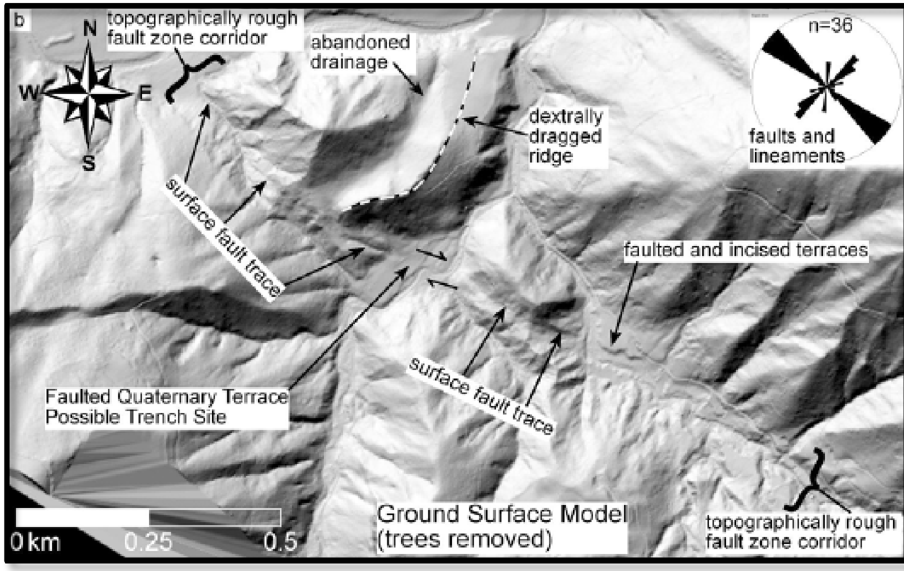


Point Cloud

x_n, y_n, z_n, i_n

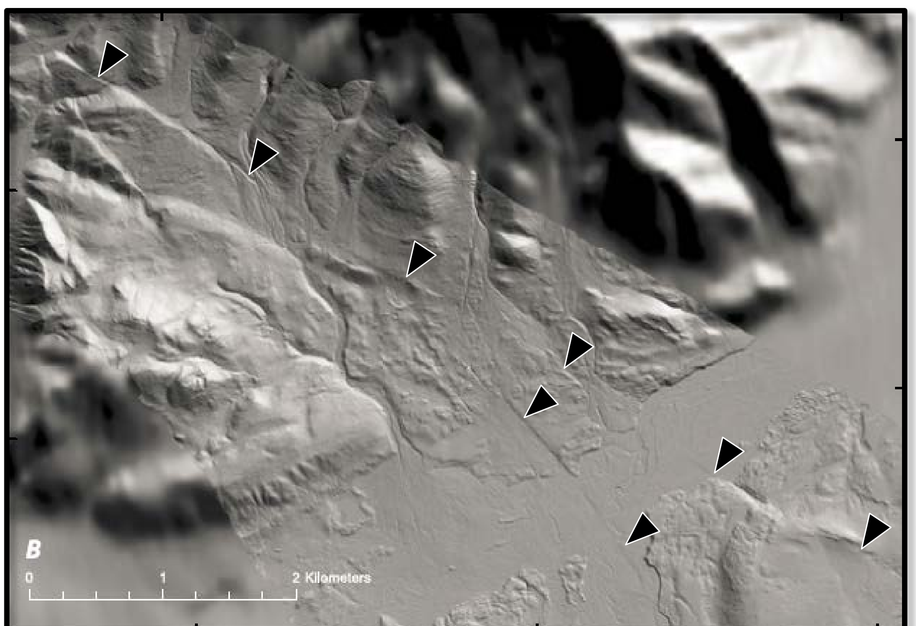
Answer science question

Identifying faults in presence of dense vegetation



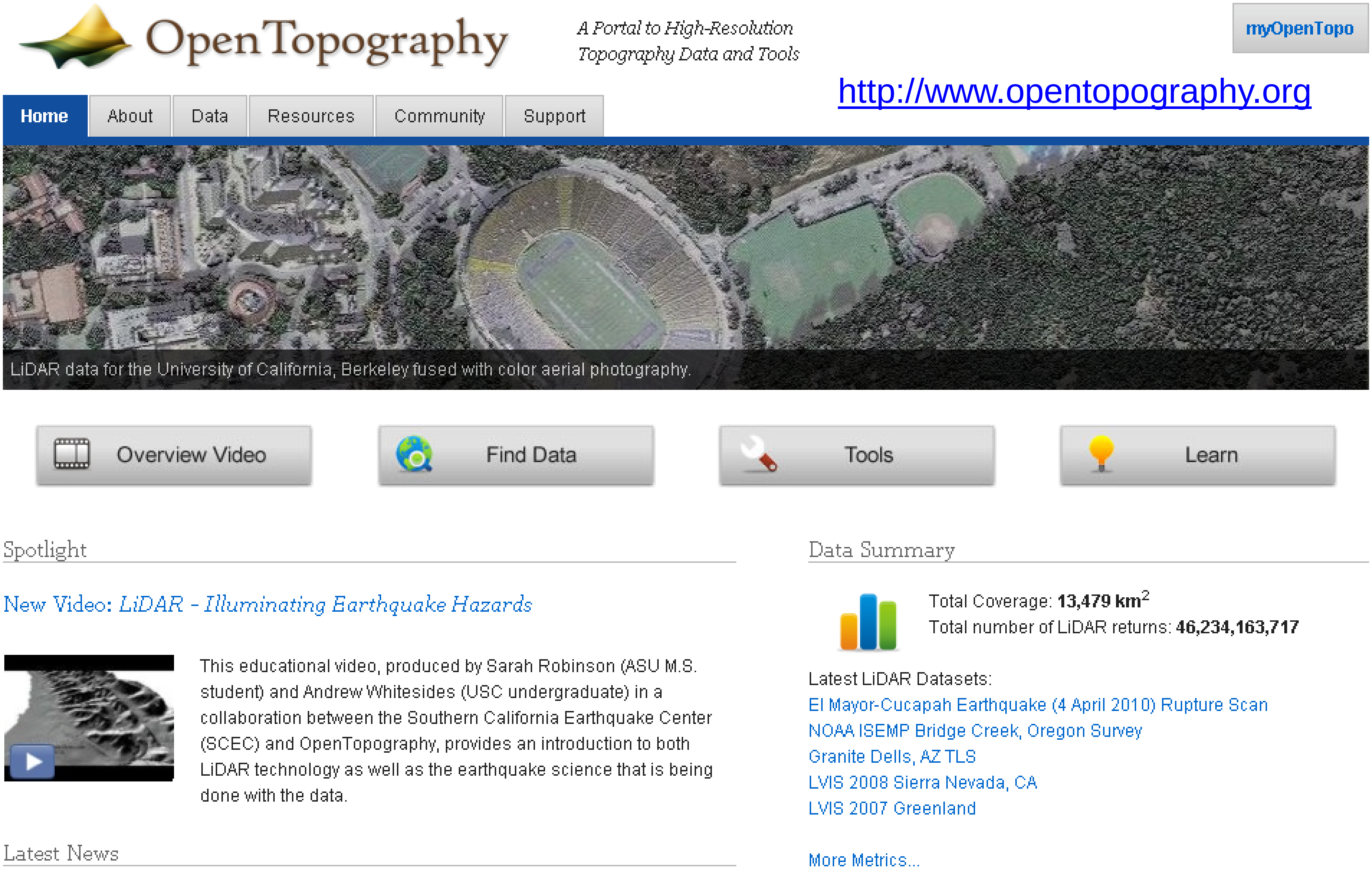
Idrija Fault (Slovenia)
Cunningham et al. (2005), *Geophys. Res. Lett.*

Tahoe-Sierra frontal fault zone
Howle et al. (2012), *Geol. Soc. Am. Bull.*



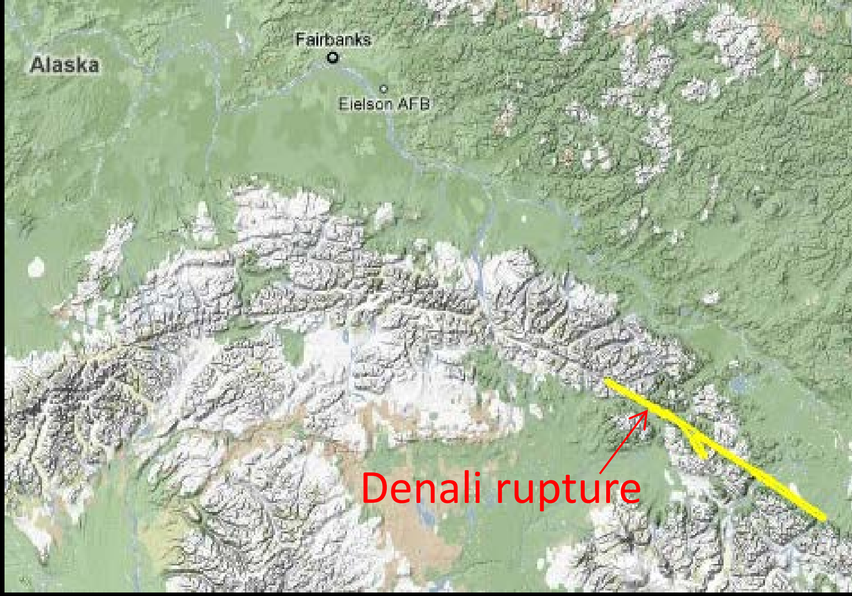
Denali fault
Schwartz et al. (2012), *J. Geophys. Res.*

-E. Nissen



http://www.opentopography.org

Facilitate community access to high-resolution, Earth science-oriented, topography data, and related tools and resources.

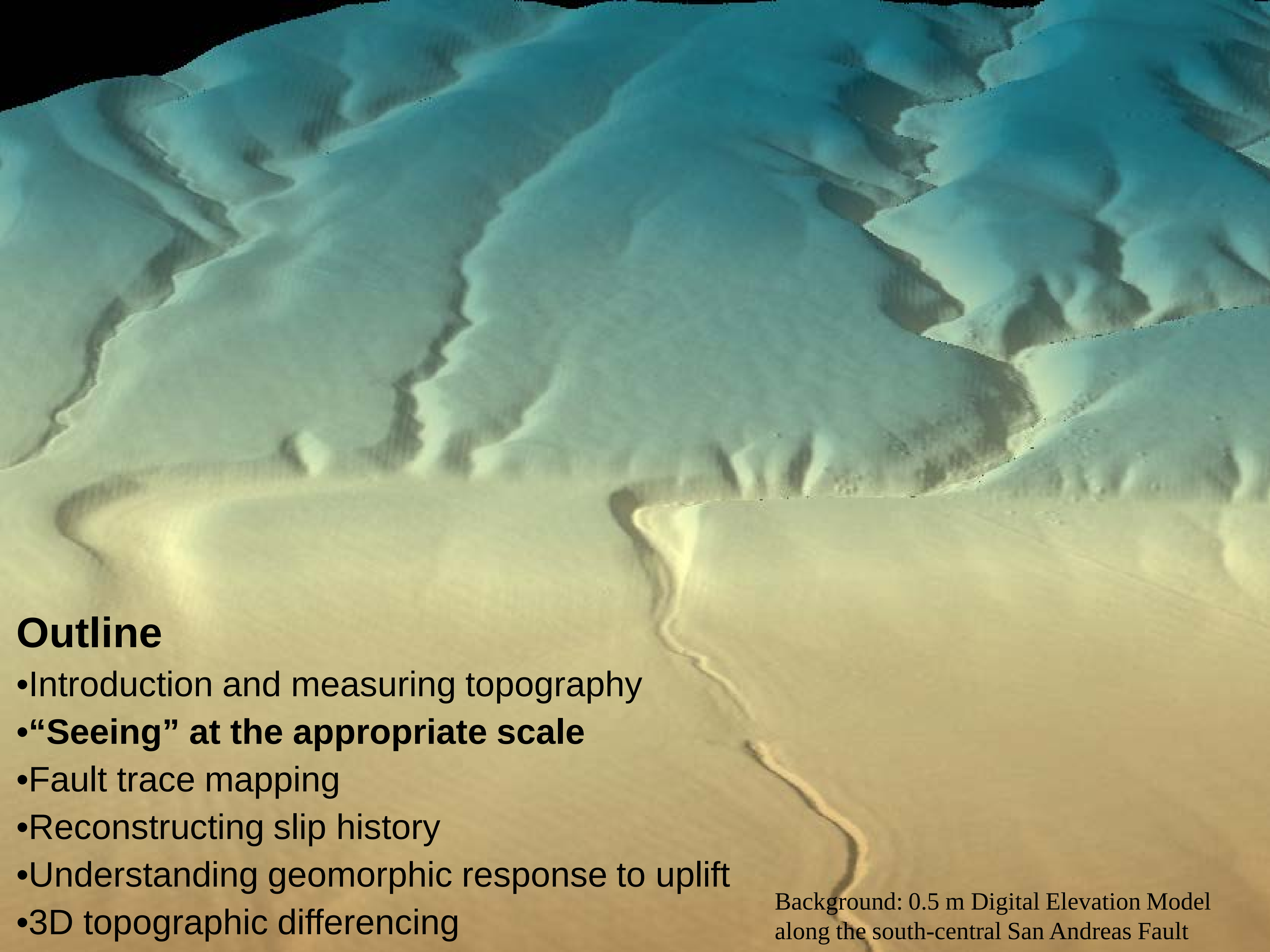


EarthScope (+) LiDAR:

Scan (at dm scale) topography along active faults to measure 10^2-10^5 yr time scale deformation and EXPLORE

See www.opentopography.org

FREE DATA!



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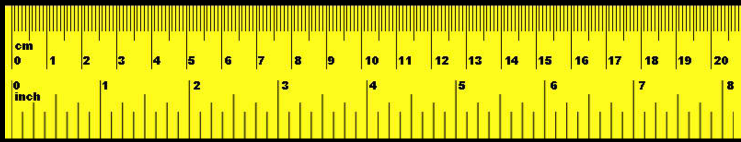
Background: 0.5 m Digital Elevation Model along the south-central San Andreas Fault

“Seeing” at the appropriate scale means measuring at the right scale



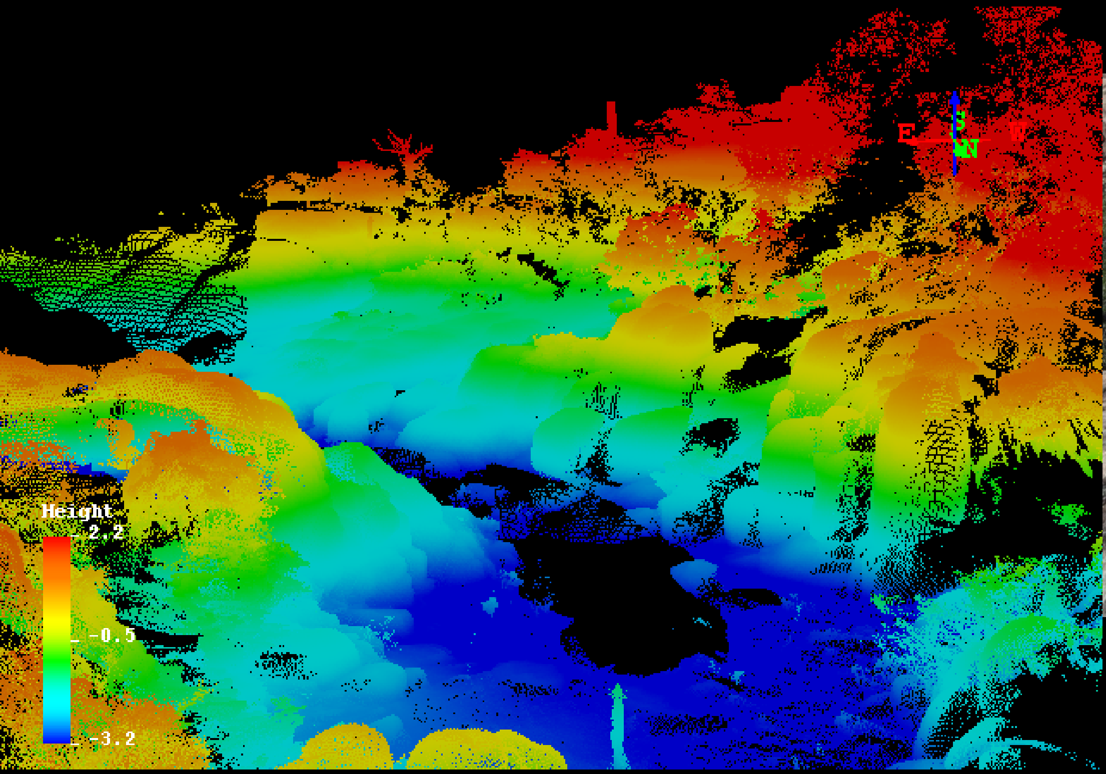
Surface processes act to change elevation through erosion and deposition while tectonic processes depress or elevate the surface directly— their record is best characterized with the right fine scale.

Applies in particular to statistical self similarity

How long is the coast of Britain?
Statistical self-similarity and fractional dimension
Science: 156, 1967, 636-638

B. B. Mandelbrot

http://en.wikipedia.org/wiki/How_Long_Is_the_Coast_of_Britain%3F_Statistical_Self-Similarity_and_Fractional_Dimension



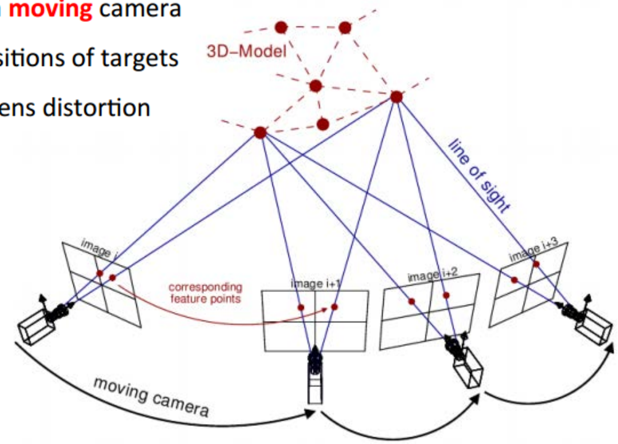
Granite Dells AZ point cloud (Haddad, et al. 2012)

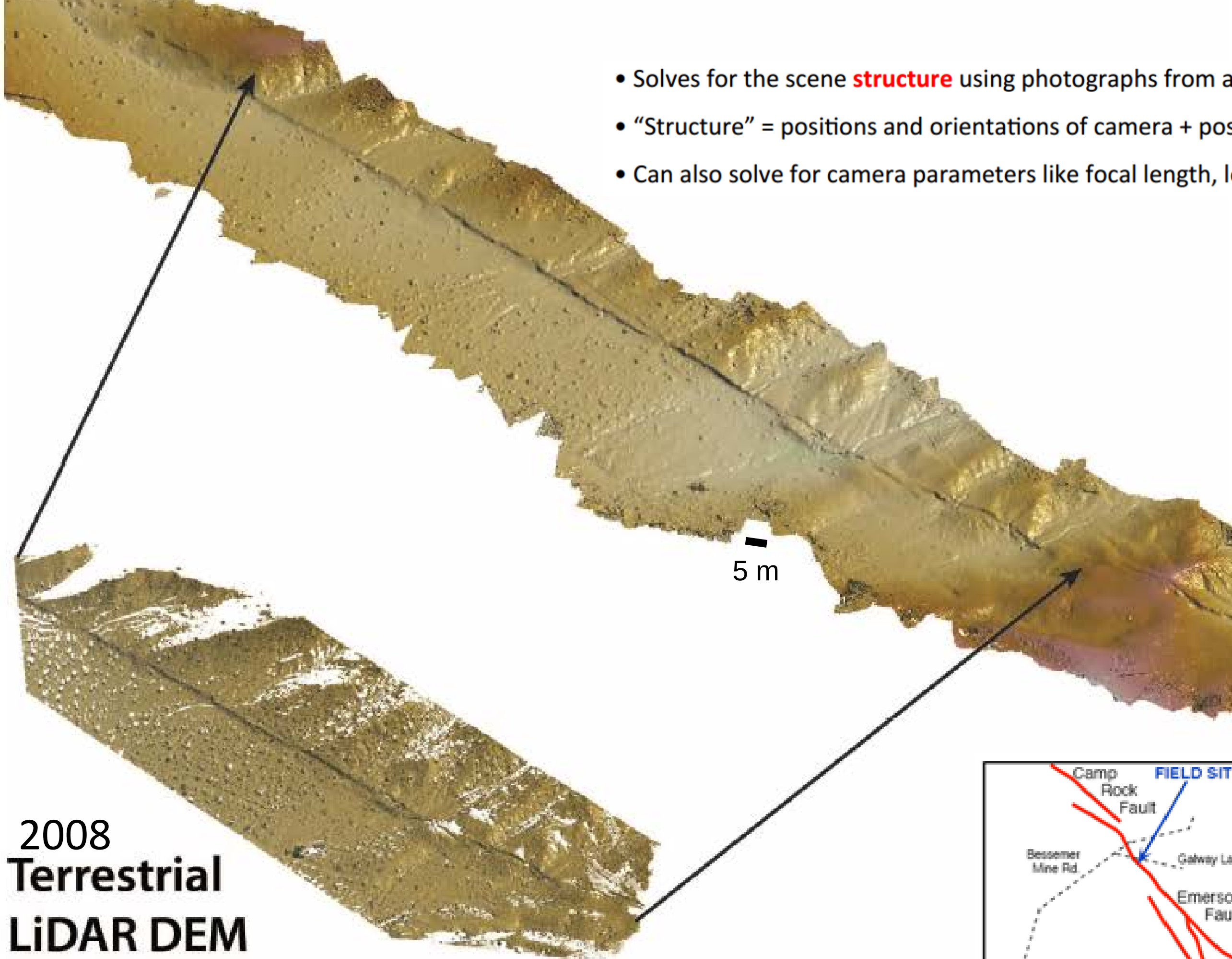
UNAVCO Terrestrial Laser Scanner

absolute measurement capability sufficient to characterize features and changes in challenging geometric arrangements

Structure from Motion

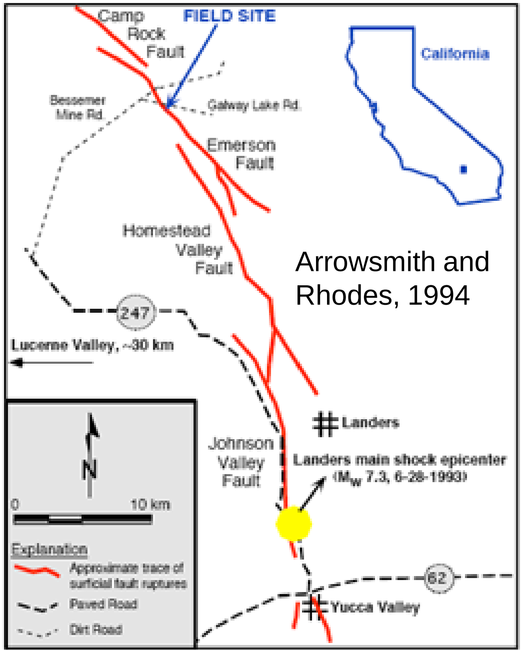
- Solves for the scene **structure** using photographs from a **moving** camera
- "Structure" = positions and orientations of camera + positions of targets
- Can also solve for camera parameters like focal length, lens distortion





2008
Terrestrial LiDAR DEM
Haddad, et al., 2012

2012
Structure from Motion DEM
Johnson, et al. 2014

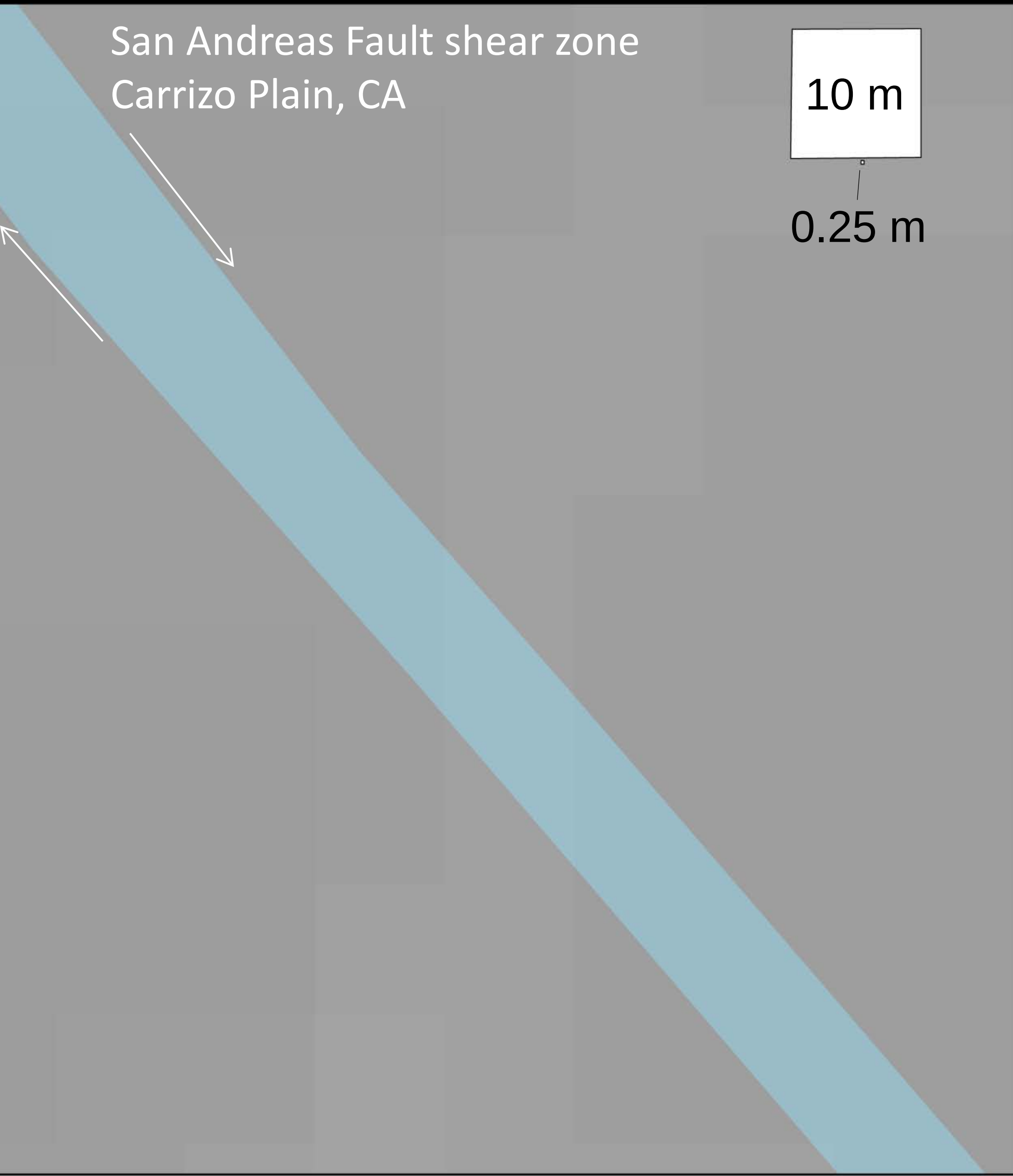


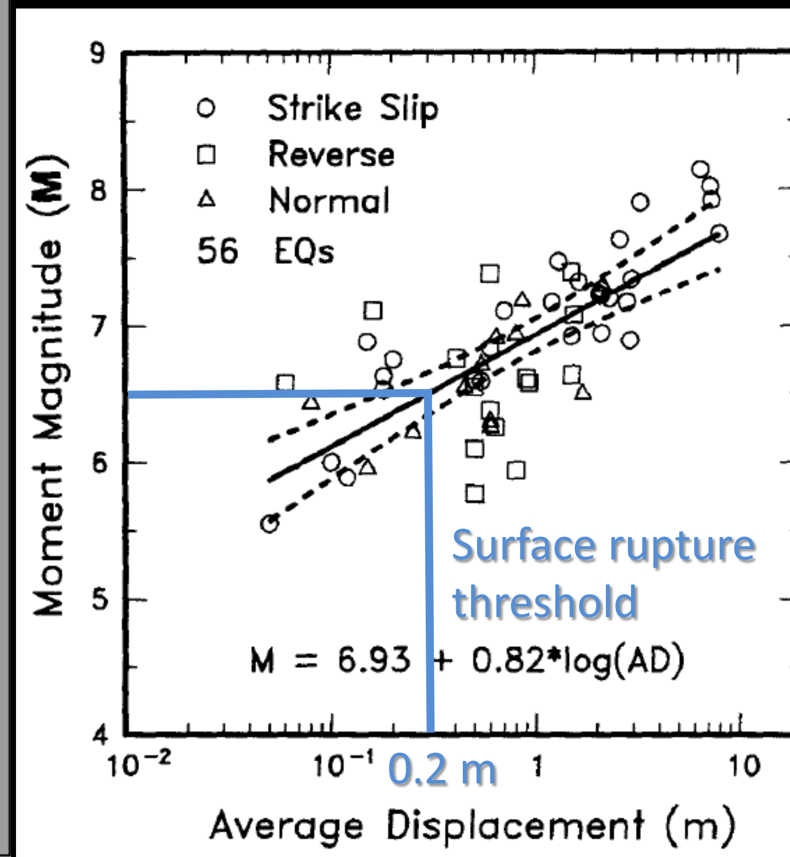
Arrowsmith and Rhodes, 1994

Landers, 1992 earthquake rupture repeated investigations on the decadal time scale: rupture zone sharp with secondary structures still evident

Measure fault slip at the appropriate scale

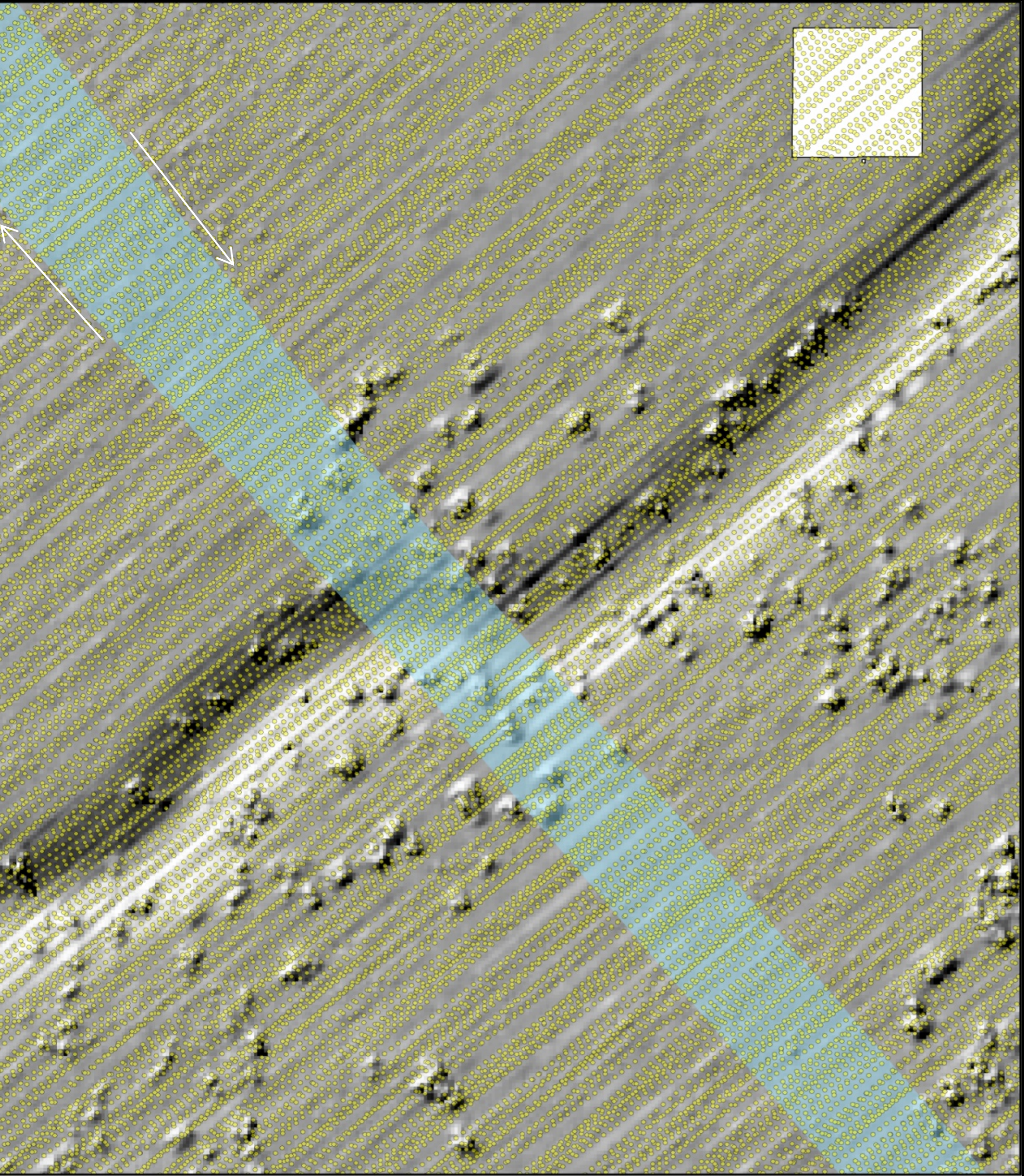
USGS NED 10 m per pixel DEM

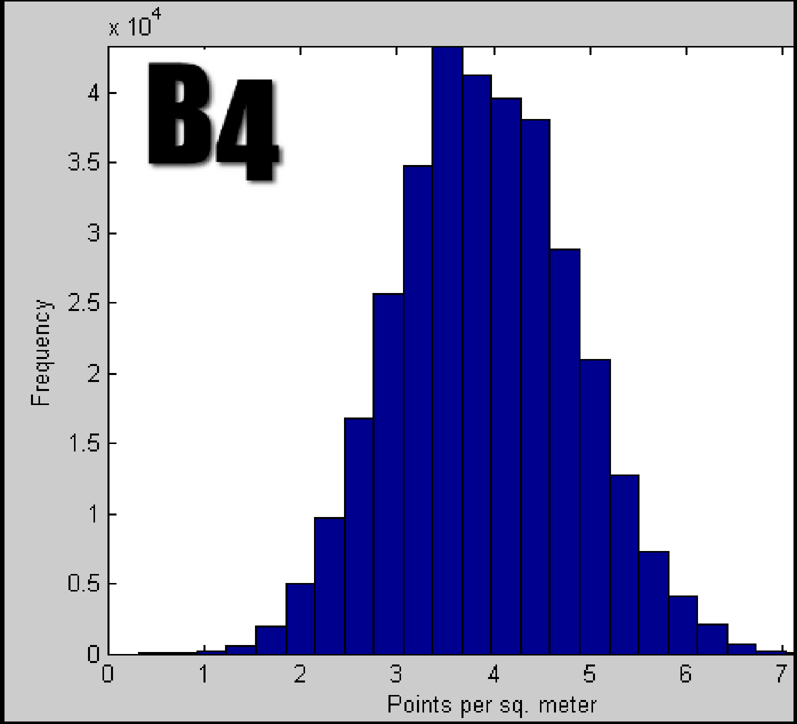




Measure fault slip at the appropriate scale

B4 LiDAR topography 0.25 m DEM

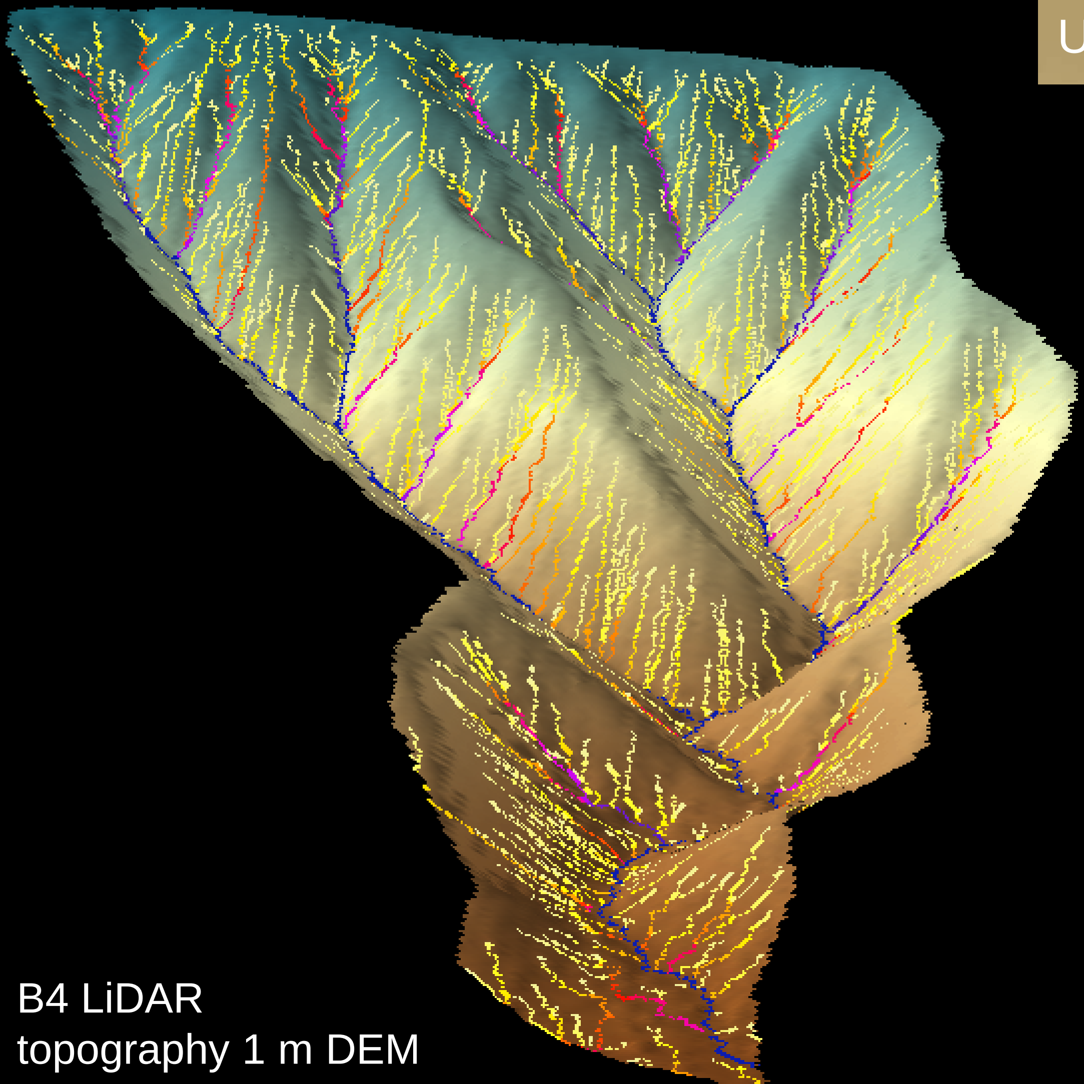




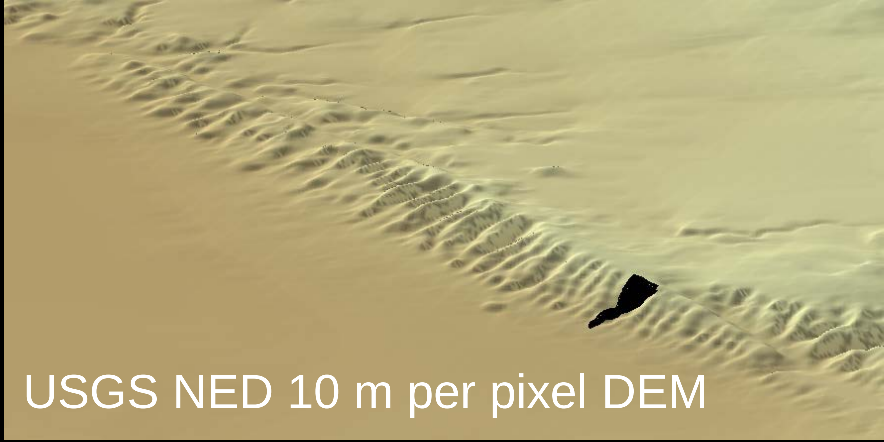
Mean ~4 shots/sq. m

Measure landscape characteristics at the appropriate scale

Drainage network-hillslope transition at 10 m^2 drainage area



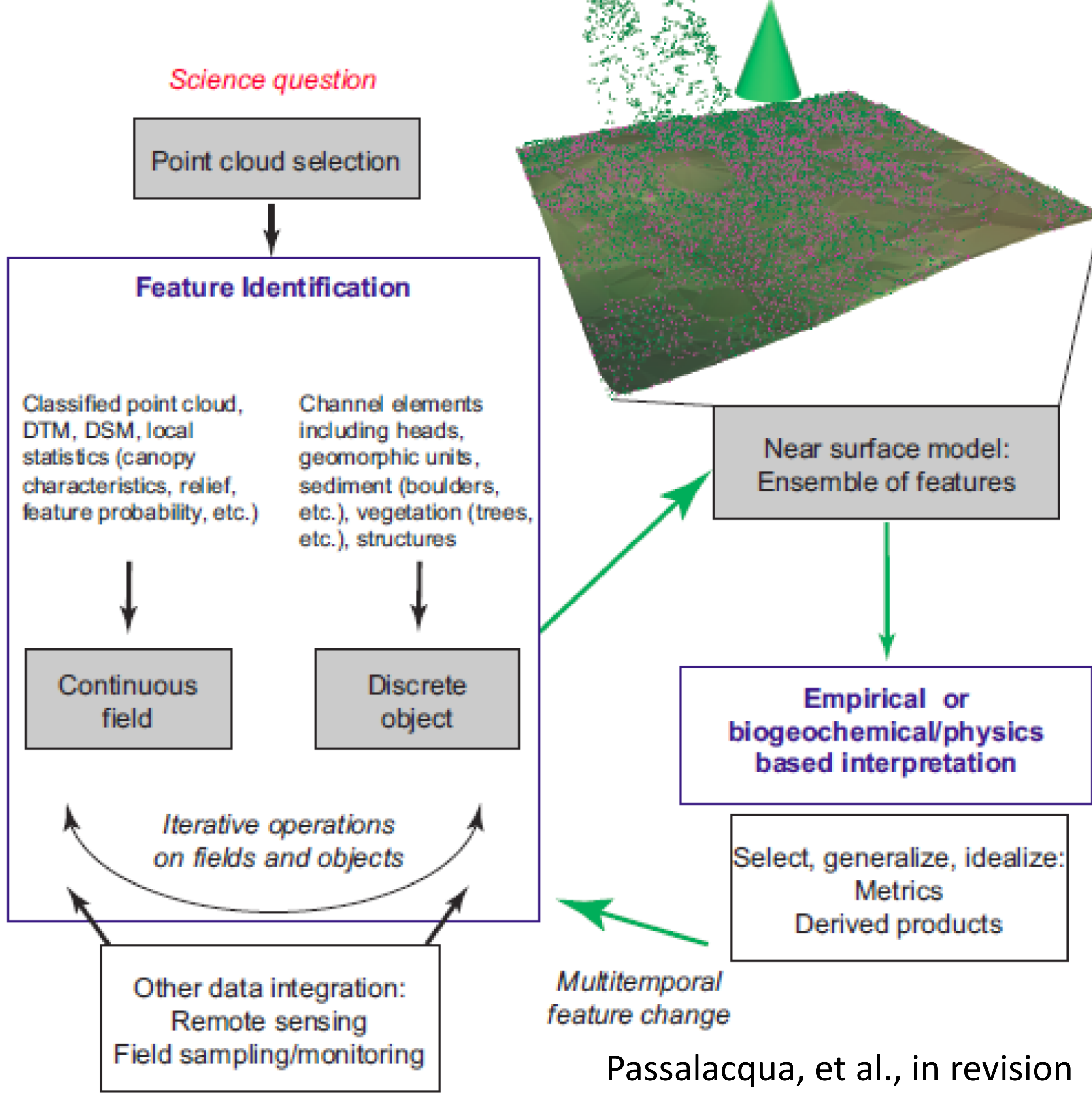
B4 LiDAR
topography 1 m DEM



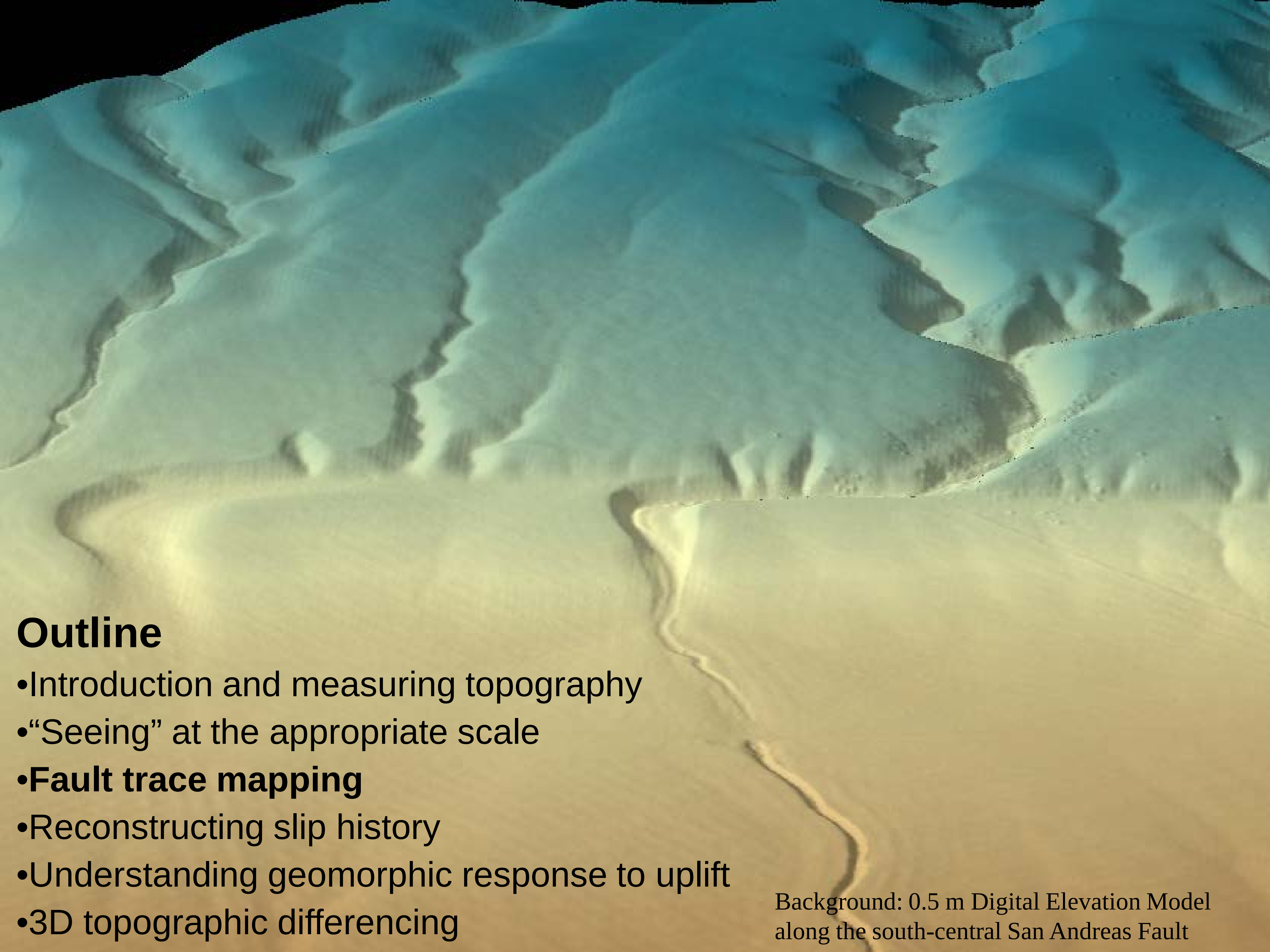
USGS NED 10 m per pixel DEM

Meter scale features

Feature Identification Workflow



Passalacqua, et al., in revision



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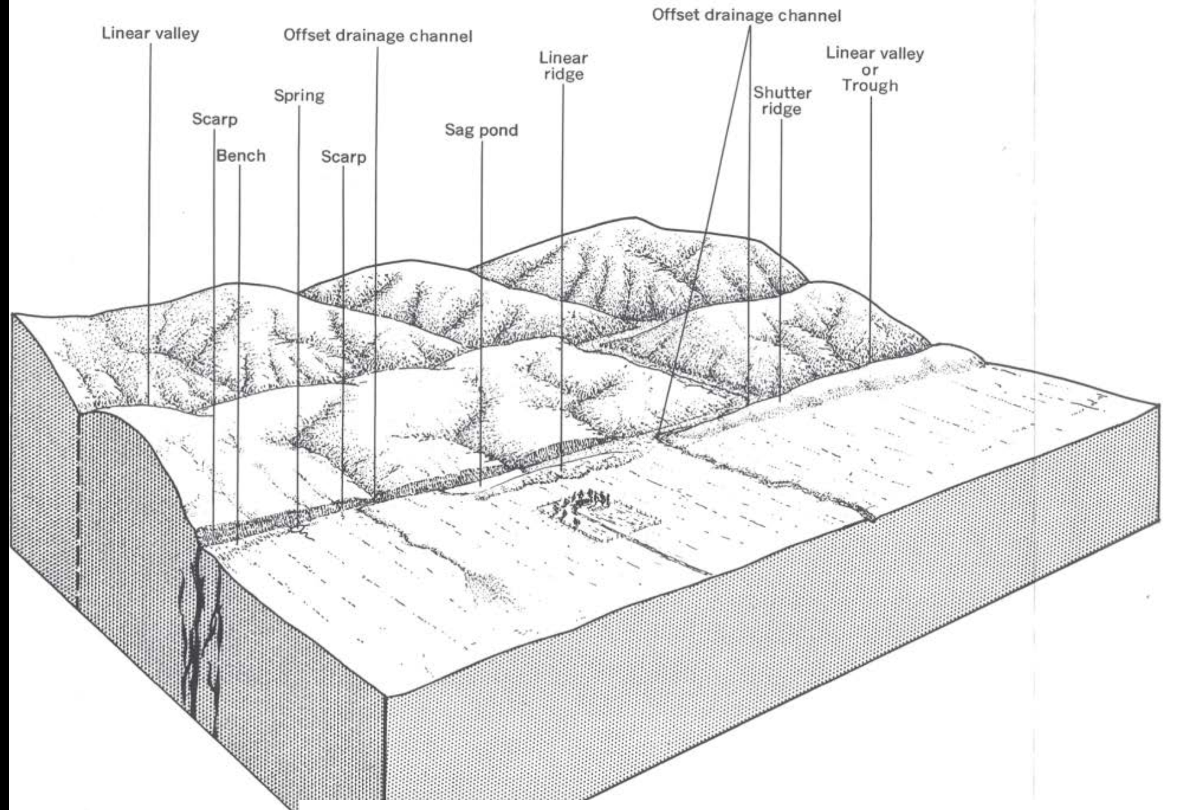
Mapping active fault traces

Classic, field, and virtual LiDAR views

An example from the Cholame section of the San Andreas Fault
Arrowsmith and Zielke, 2009



Vedder and Wallace, 1970 and numerous others

Explanation for fault strip mapping

Vedder and Wallace, 1970

- Local features with annotation
- Regional features
- Recently active breaks, certain
- Recently active breaks, less obvious
- Ponds and lakes

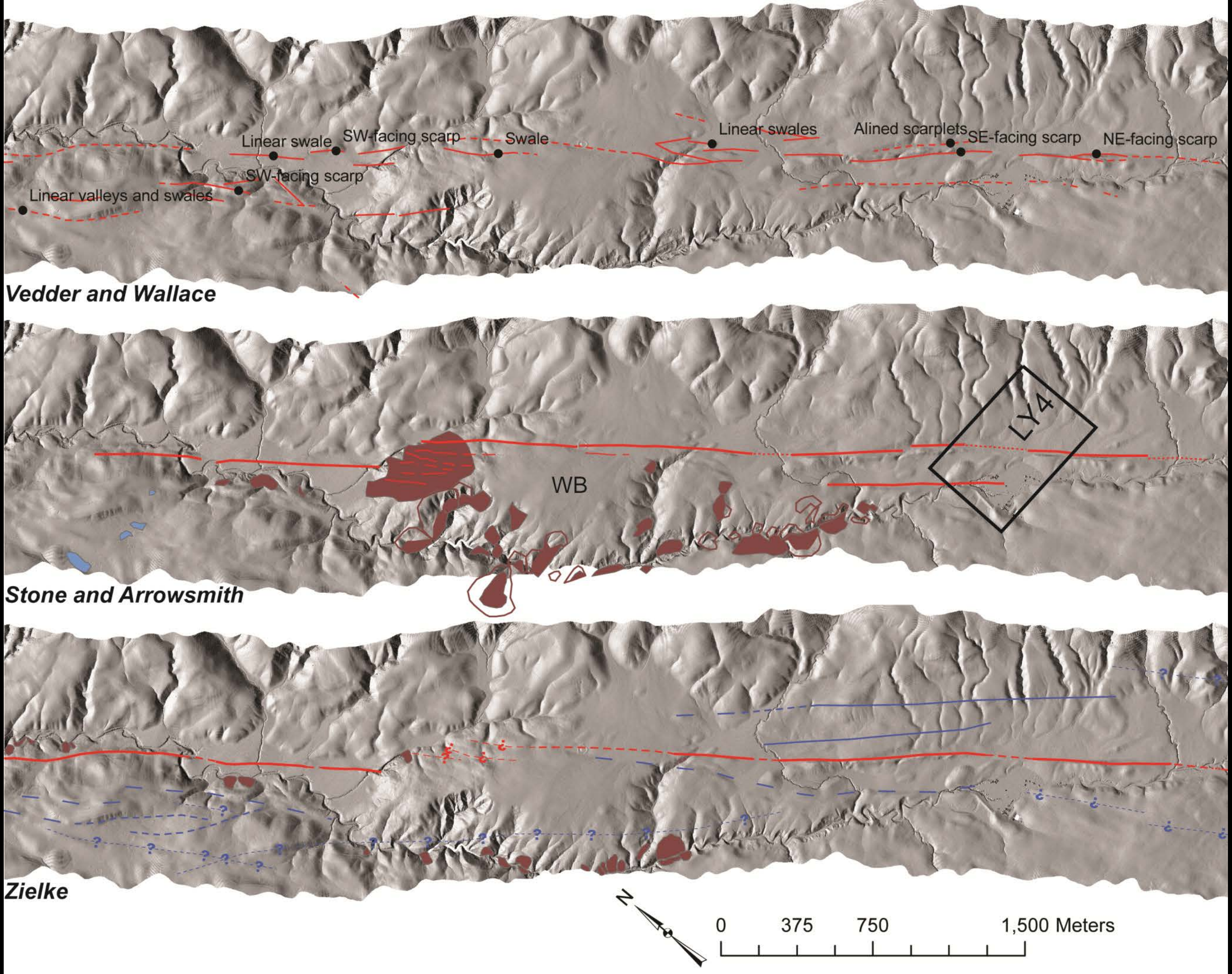
Stone and Arrowsmith

- Fault trace
- Fault trace, concealed
- Fault trace, inferred
- Lineament
- Landslide deposit
- Landslide scarp
- Sag

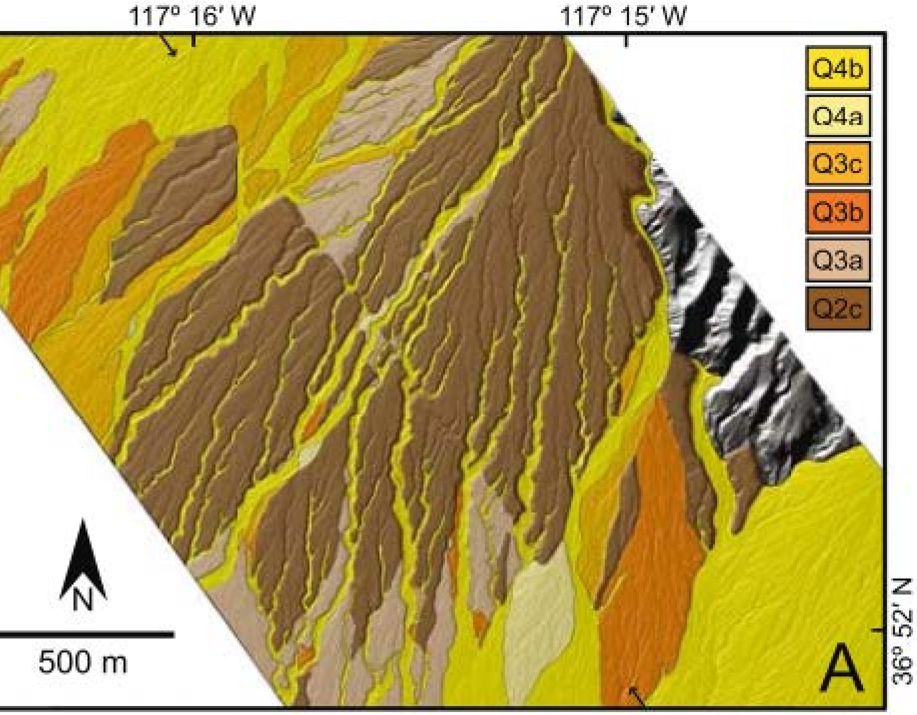
Zielke, this study

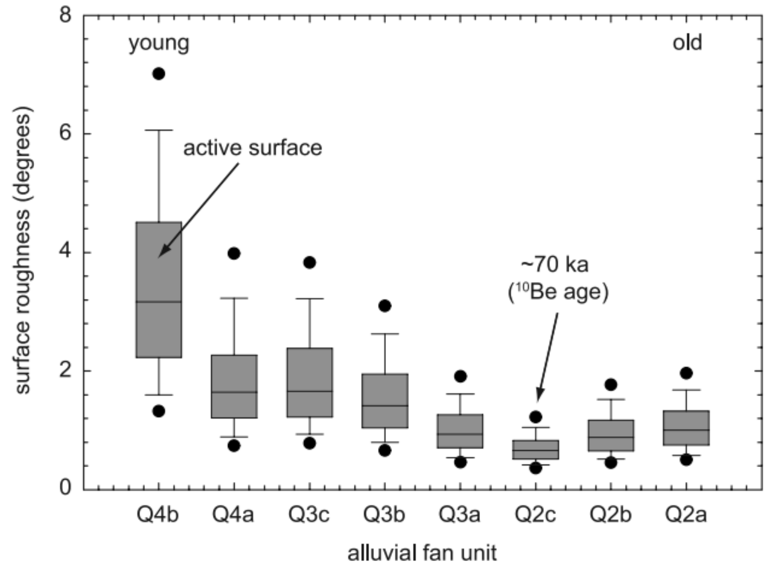
Fault traces: red for main trace, blue for secondary traces

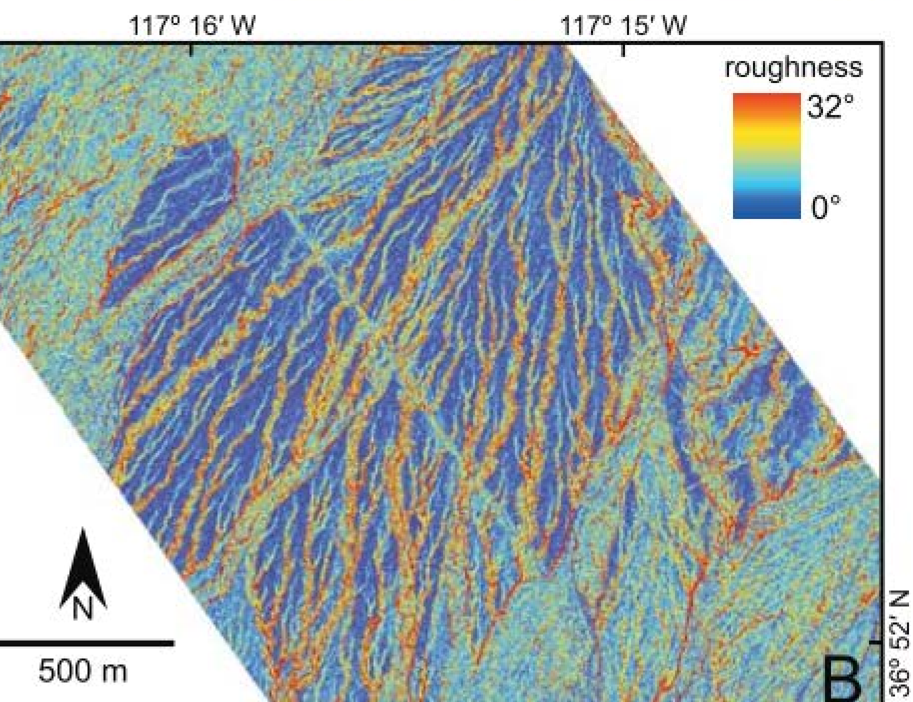
- Fault trace, certain
- Fault trace, inferred
- ? Fault trace, queried
- Fault trace, uncertain
- Landslide deposit and scarp



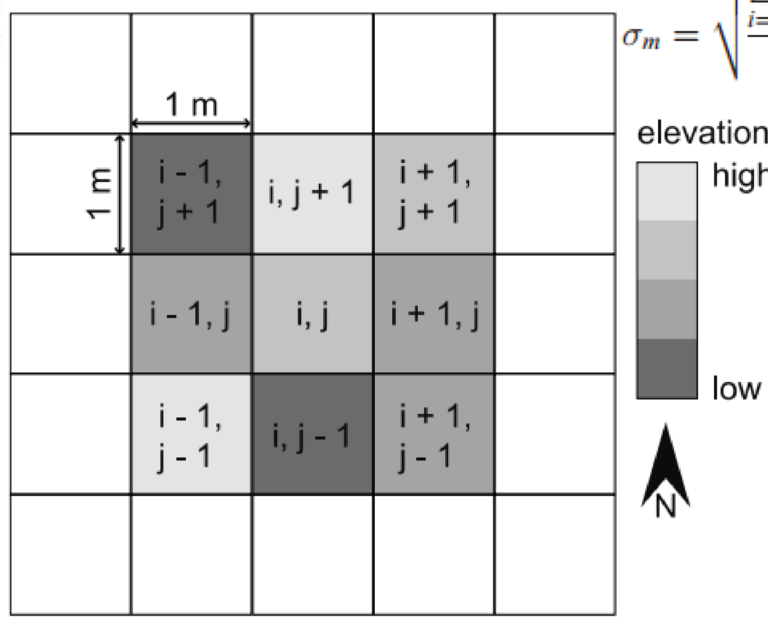
Linear swale
SW-facing scarp
Swale
Linear swales
Alined scarplets
SE-facing scarp
NE-facing scarp
SW-facing scarp
Linear valleys and swales
Vedder and Wallace
LY4
WB
Stone and Arrowsmith
Zielke
N
0
375
750
1,500 Meters





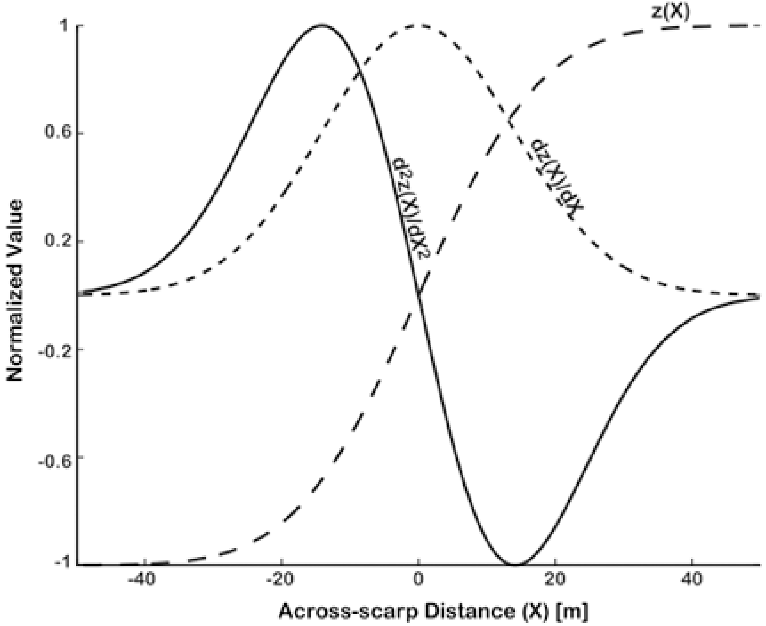


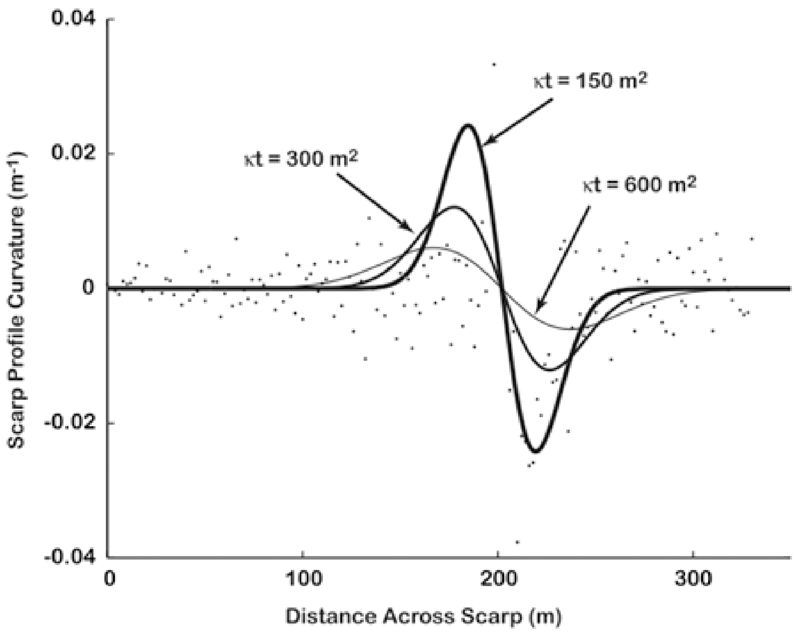
$$\sigma_m = \sqrt{\frac{\sum_{i=1}^{n} (m_i - \overline{m})^2}{n}},$$

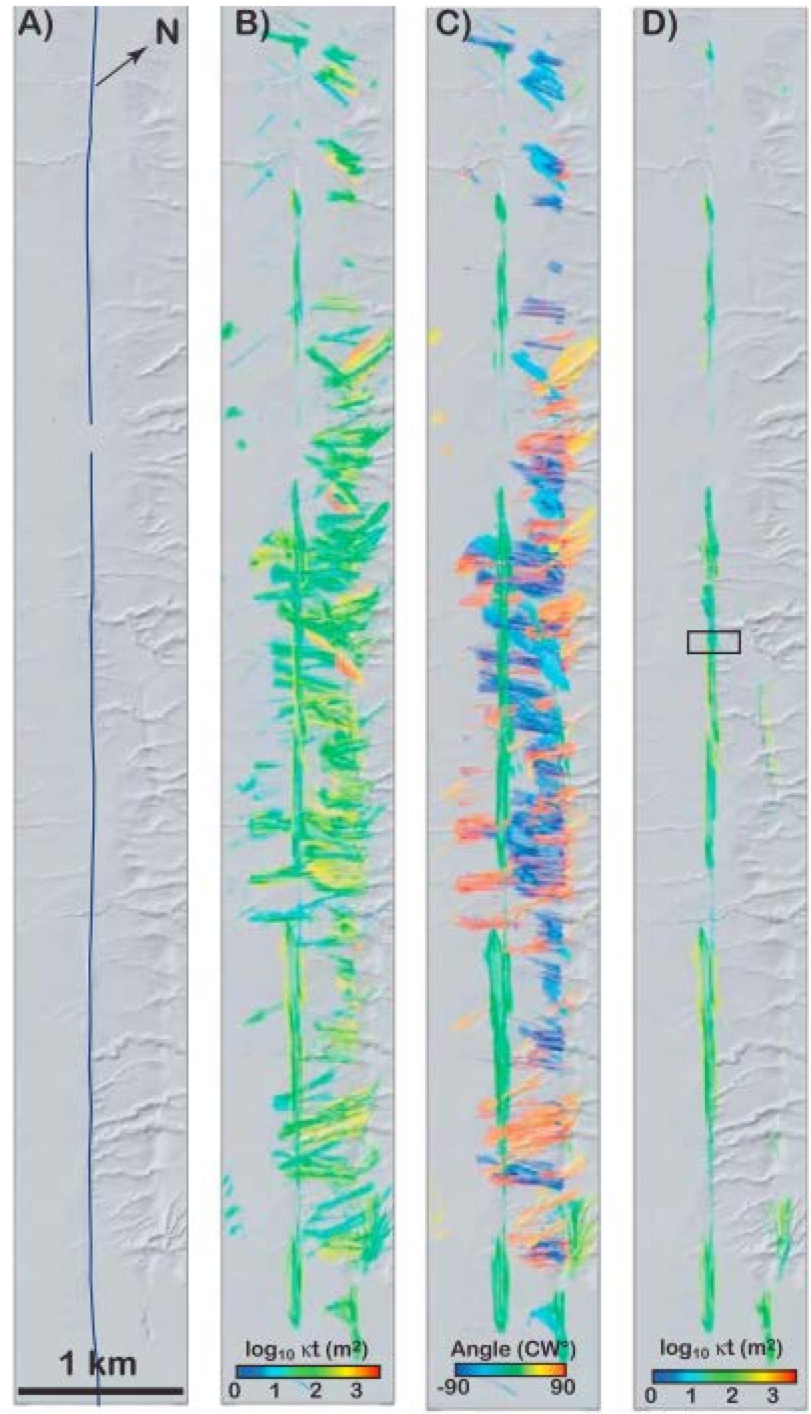


Characterizing arid region alluvial fan surface roughness with airborne laser swath mapping digital topographic data

Kurt L. Frankel[1] and James F. Dolan[1] JGR, 2007





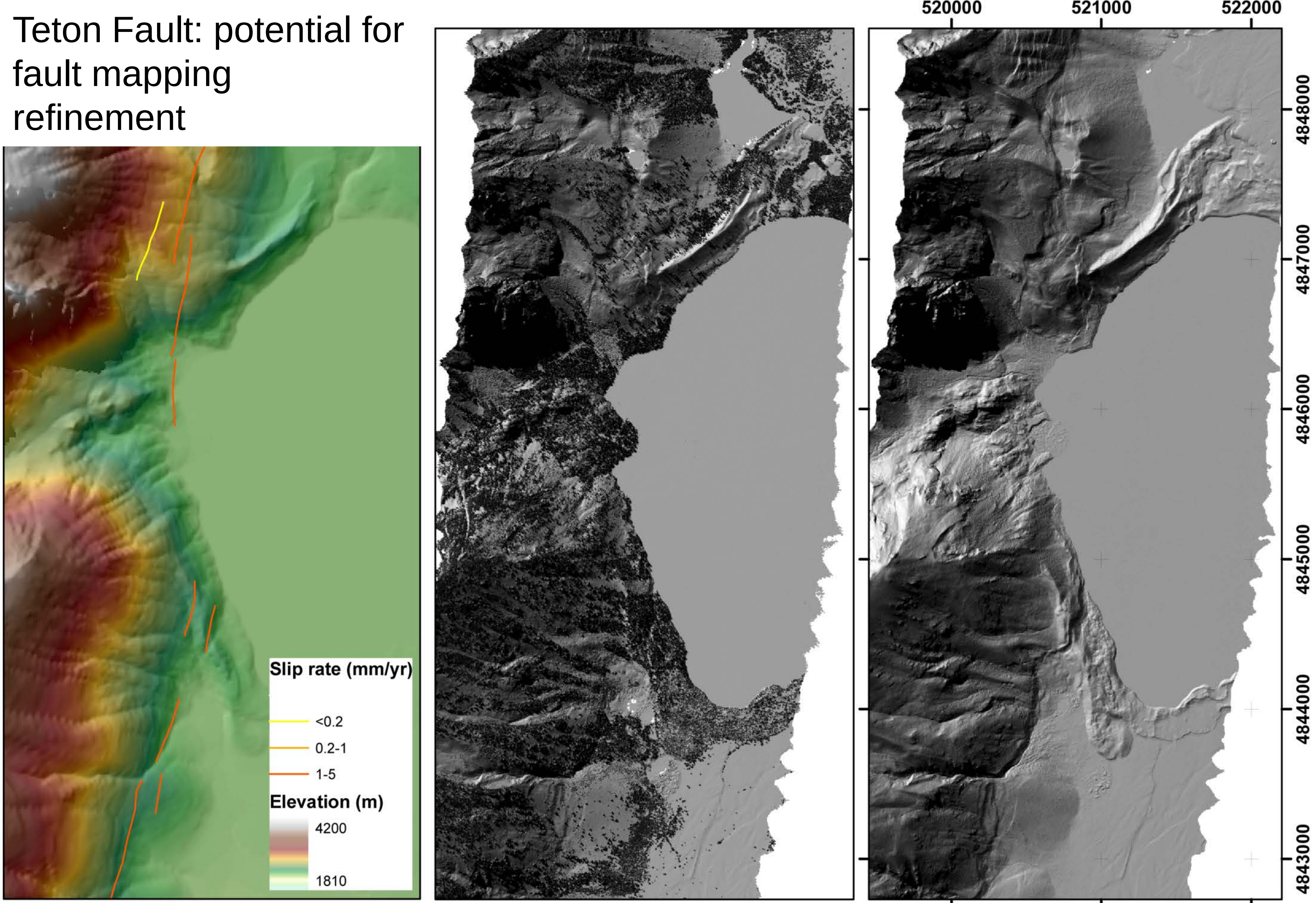


Morphologic dating of fault scarps using airborne laser swath mapping (ALSM) data

GRL, 2010

G. E. Hilley,[1] S. DeLong,[2] C. Prentice,[2] K. Blisniuk,[3] and JR. Arrowsmith[4]

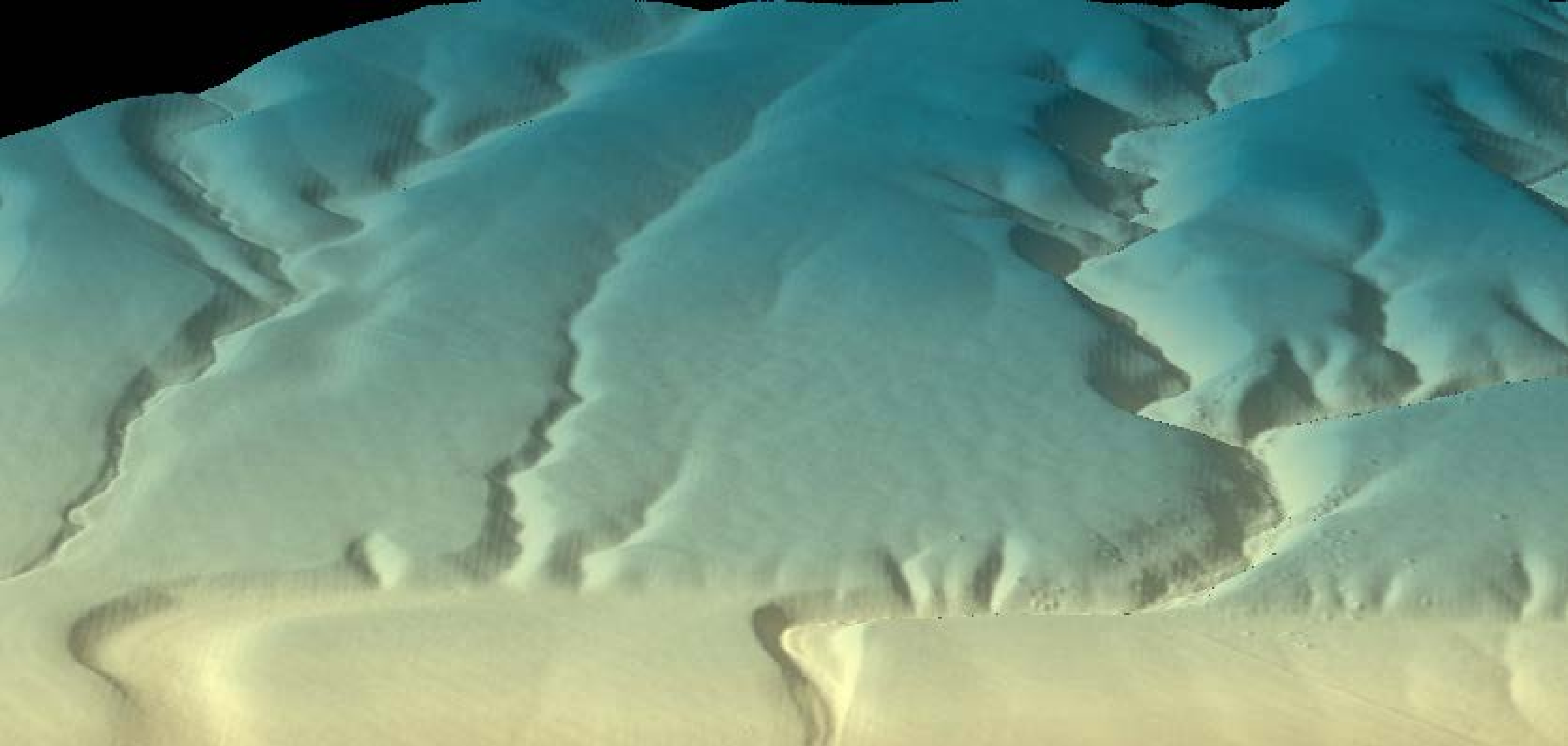
Teton Fault: potential for fault mapping refinement



USGS National Elevation Dataset and Quaternary Faults

1 m EarthScope unfiltered DEM

1 m EarthScope filtered DEM



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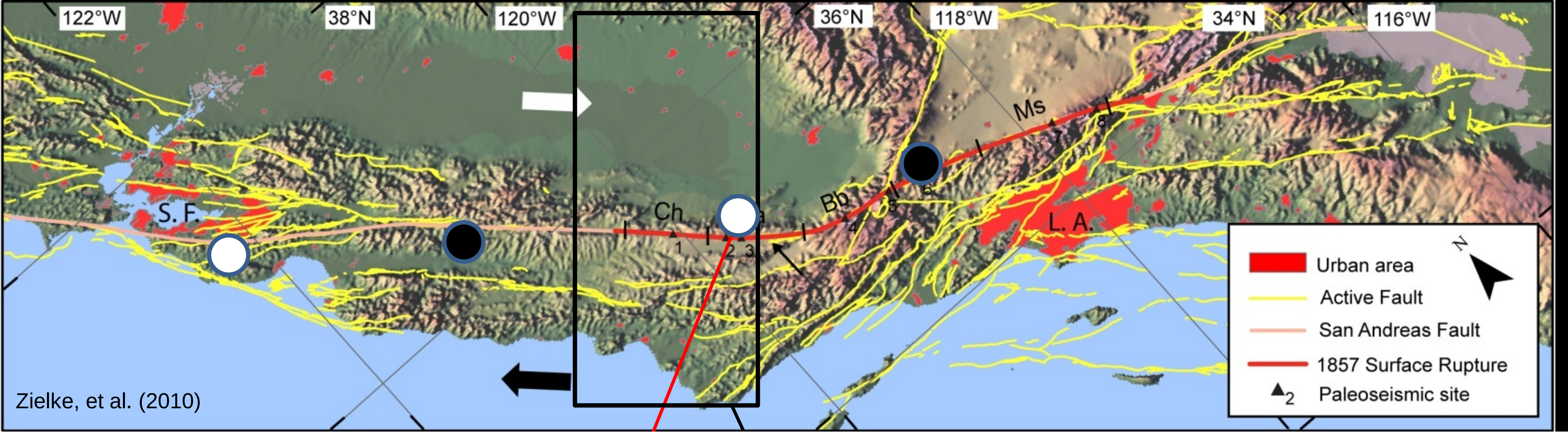
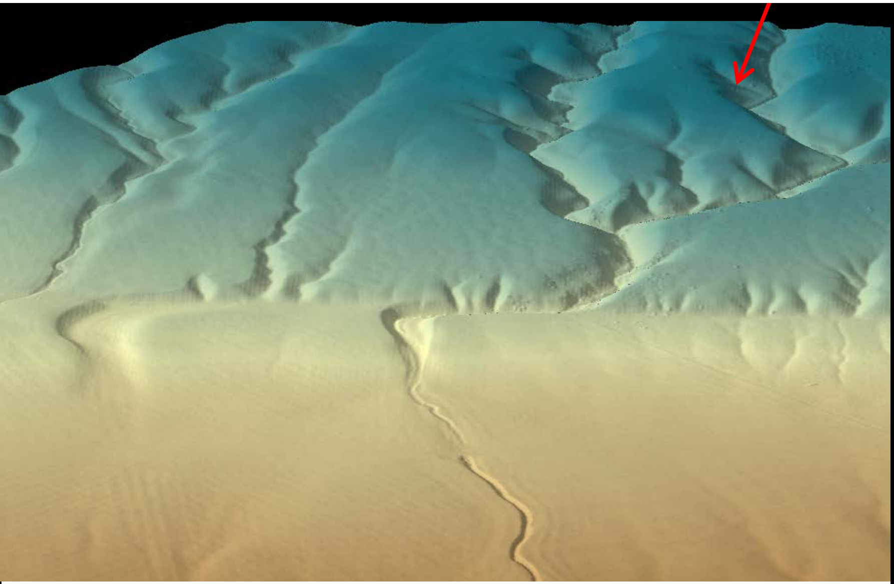
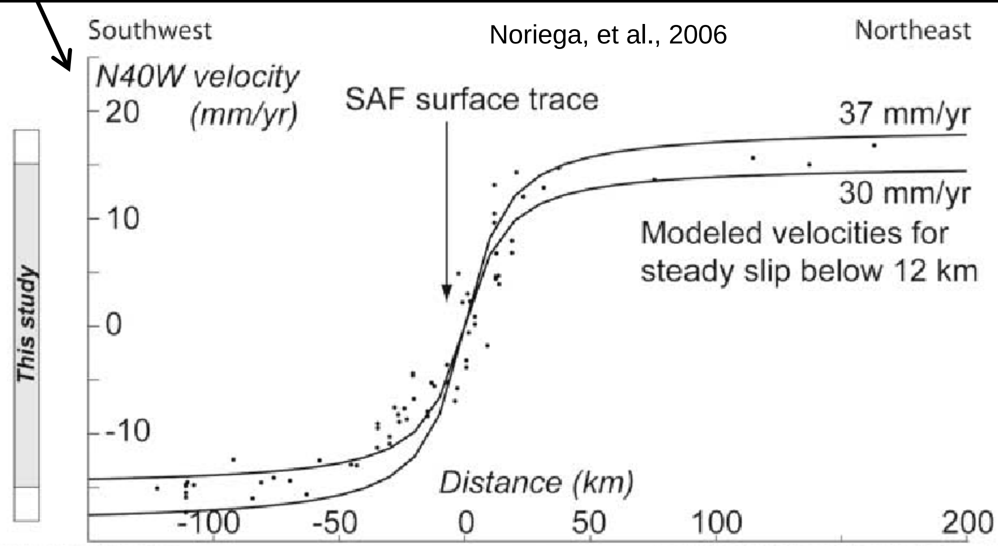


Long term offset: 320 km since 24 Ma along major fault within plate boundary fault array

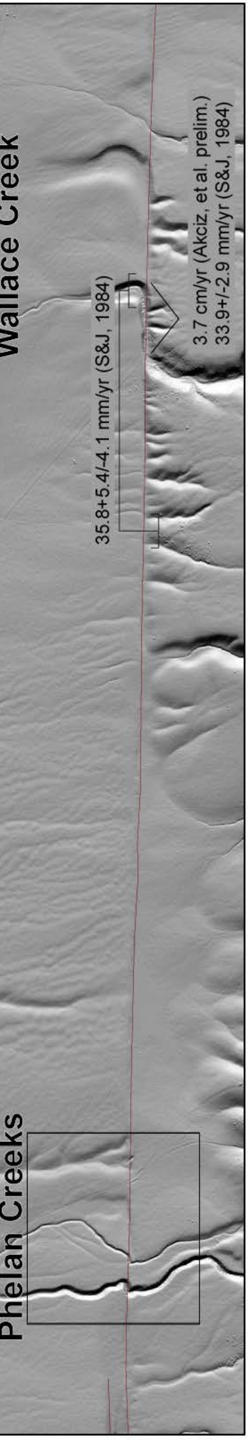


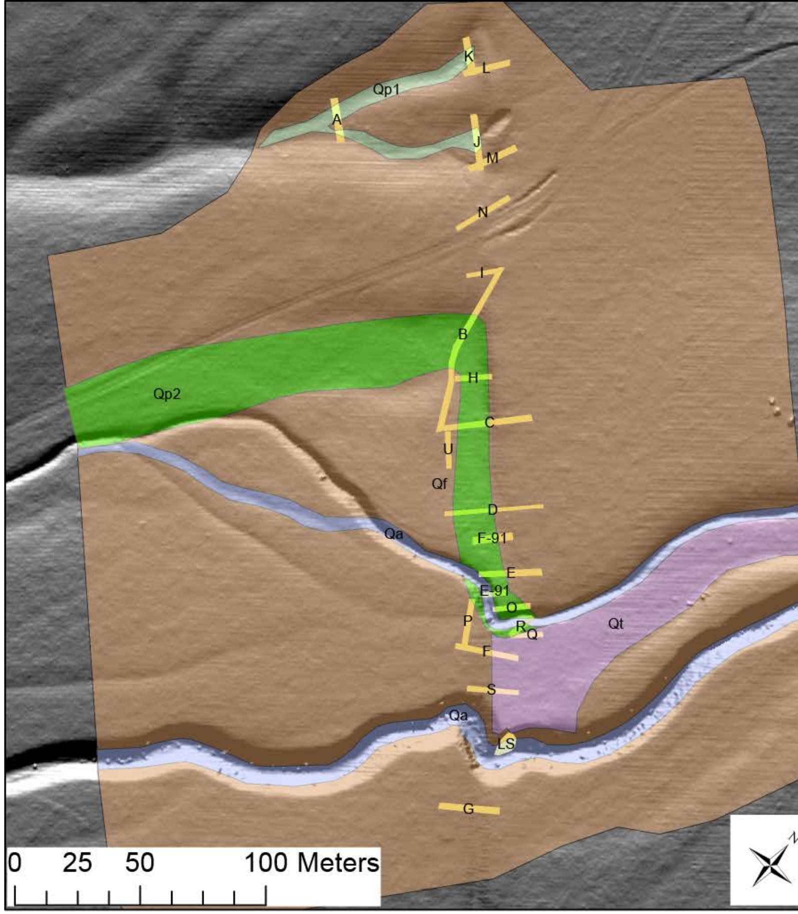
Slip rate of 34 mm/yr localized across <10m since at least 13.5 ka Sieh and Jahns (1984)

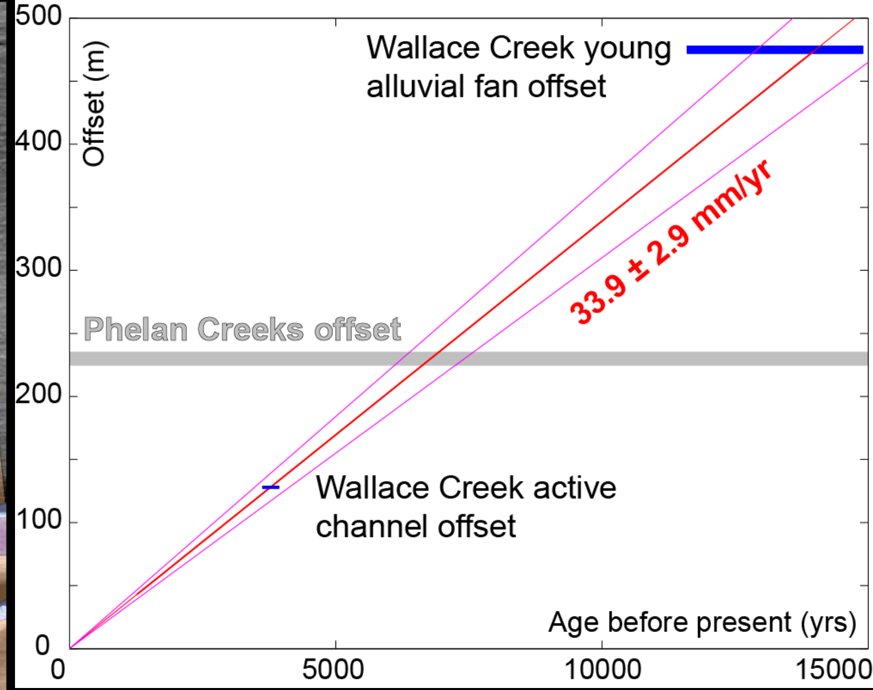


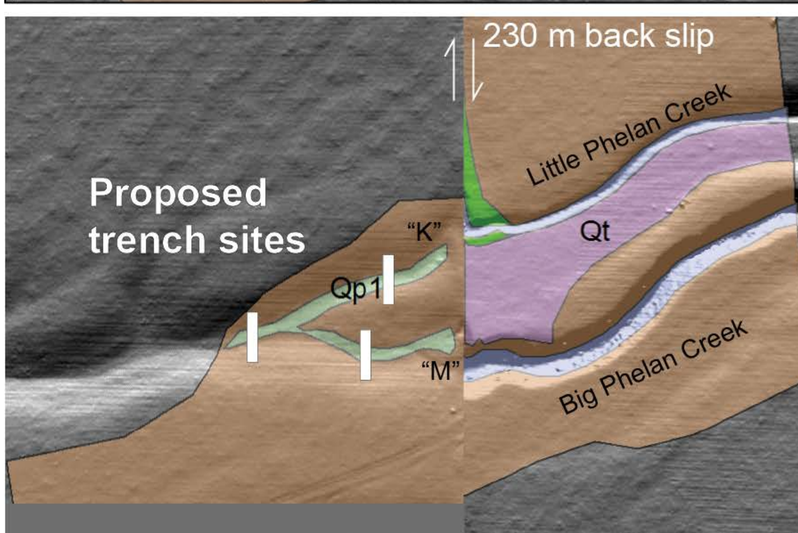
Steady strain accumulation by deep slip at 30-37 mm/yr over decadal time scale from geodesy

Steady strain accumulation and release along south-central San Andreas Fault

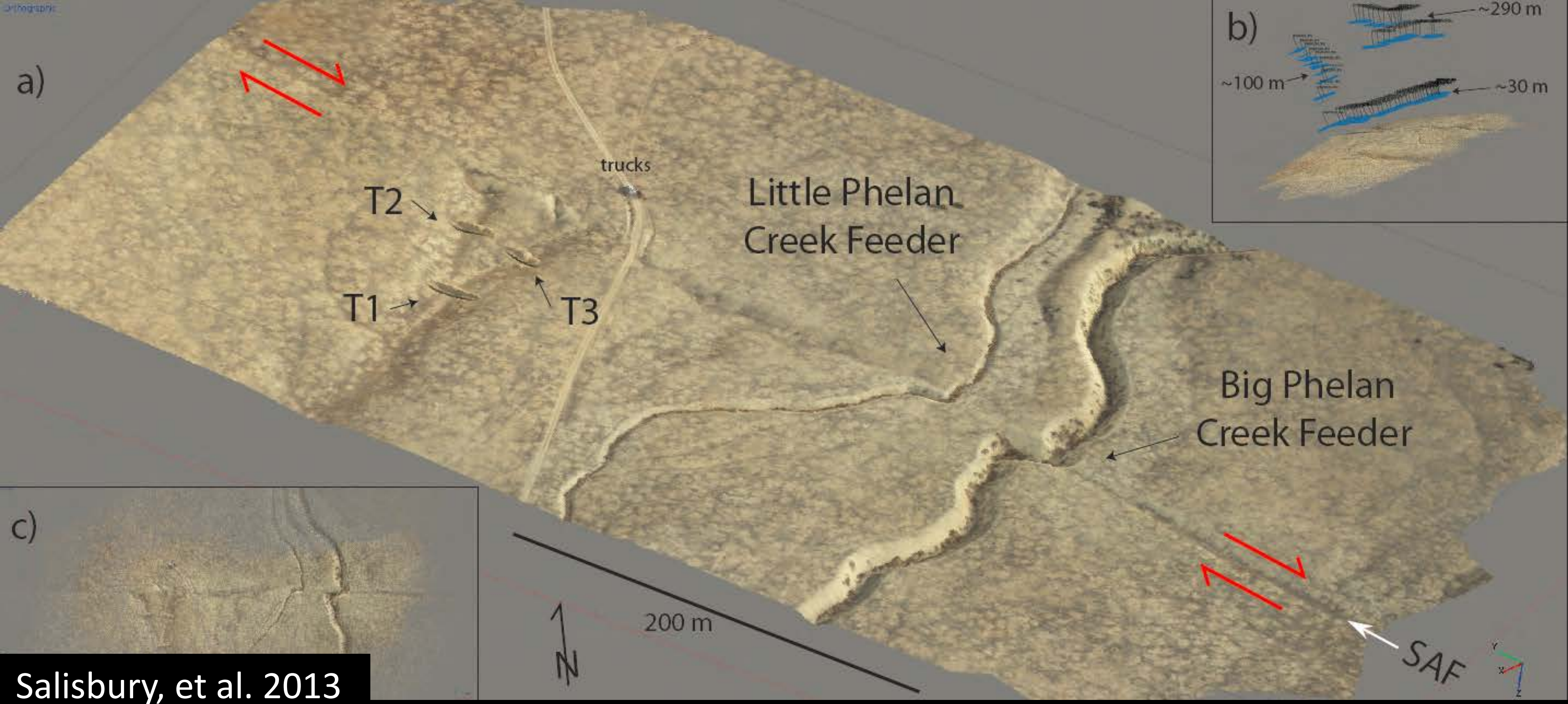








Opportunity to to update the central San Andreas fault slip rate at Phelan Creeks. How does it compare with the rate determinations from Wallace Creek?



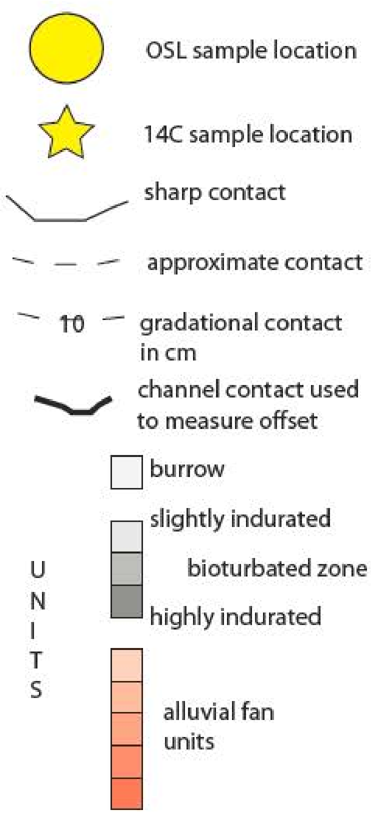
Salisbury, et al. 2013

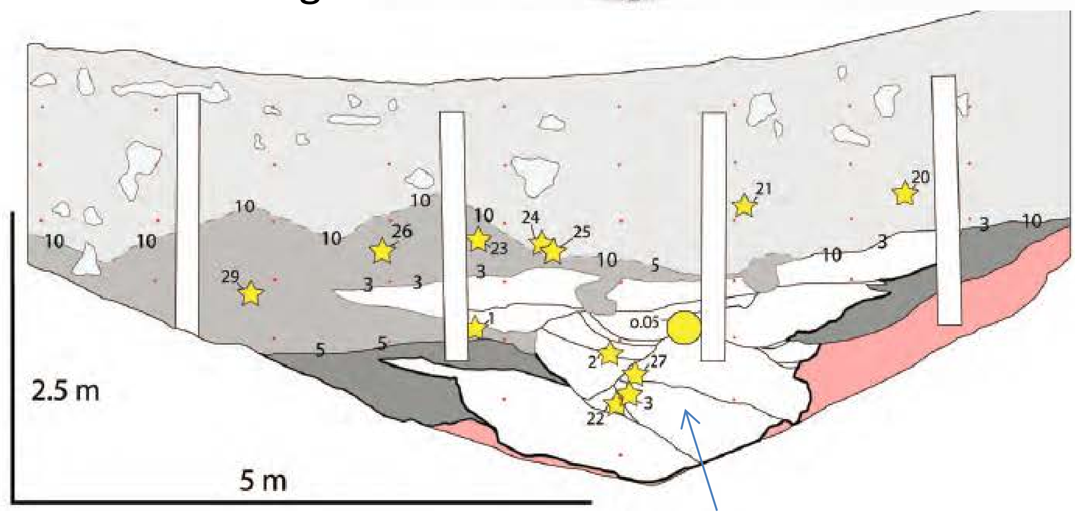
Phelan Creeks:
Structure from Motion topography and image texture

Phelan Creeks

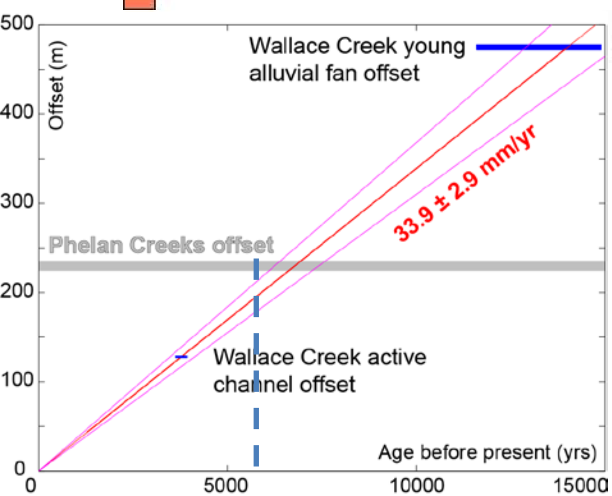
b) T3east

SfM trench image

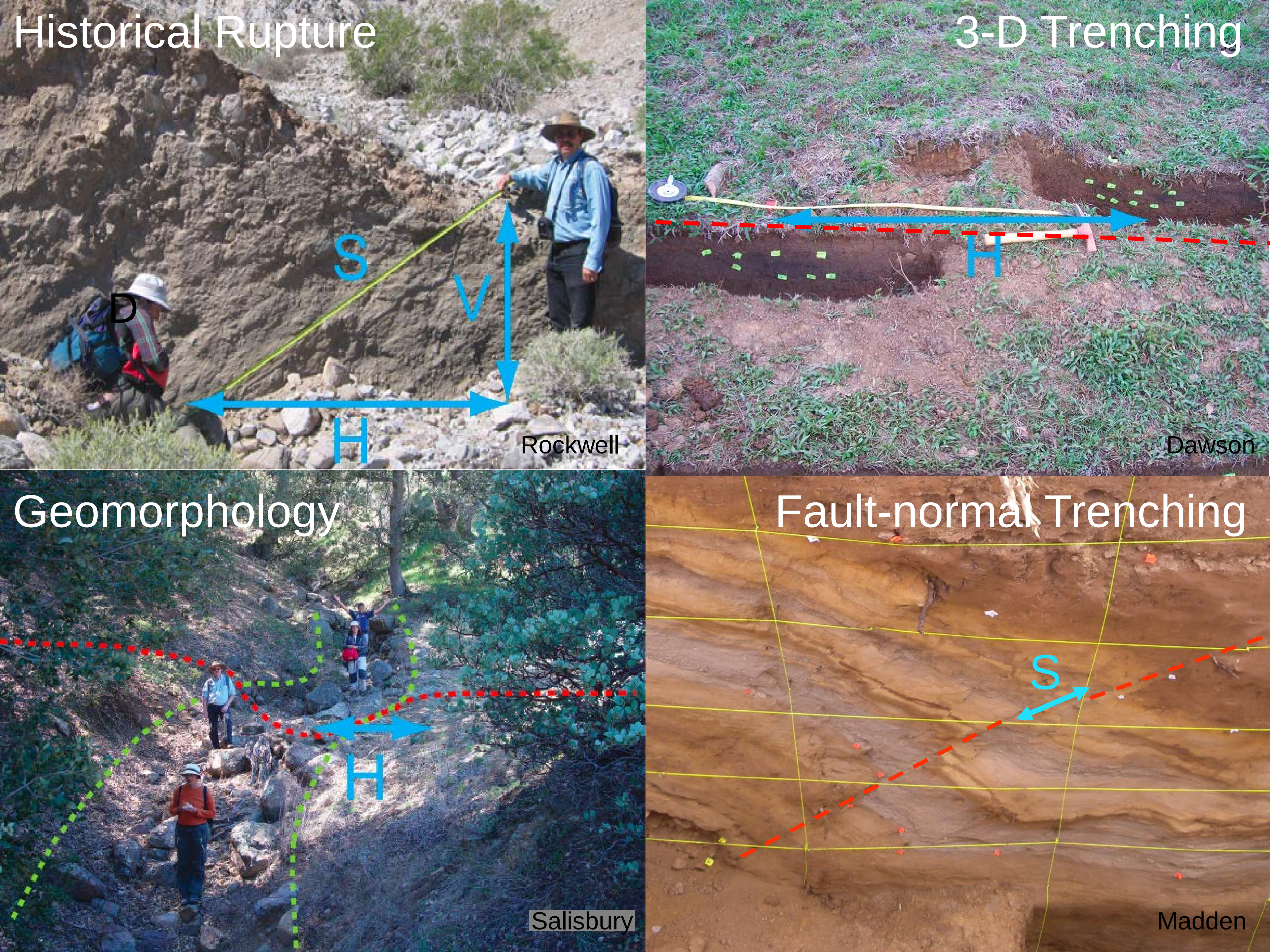




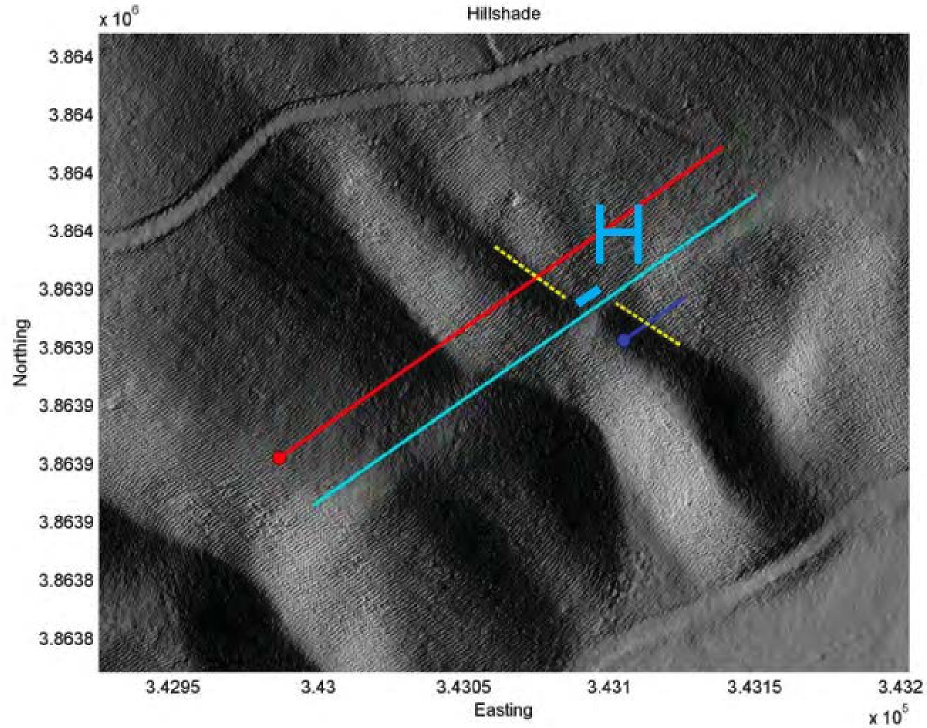
preliminary OSL age estimates of 5.6 +/- 0.3 and 6.0 +/- 0.4 ka

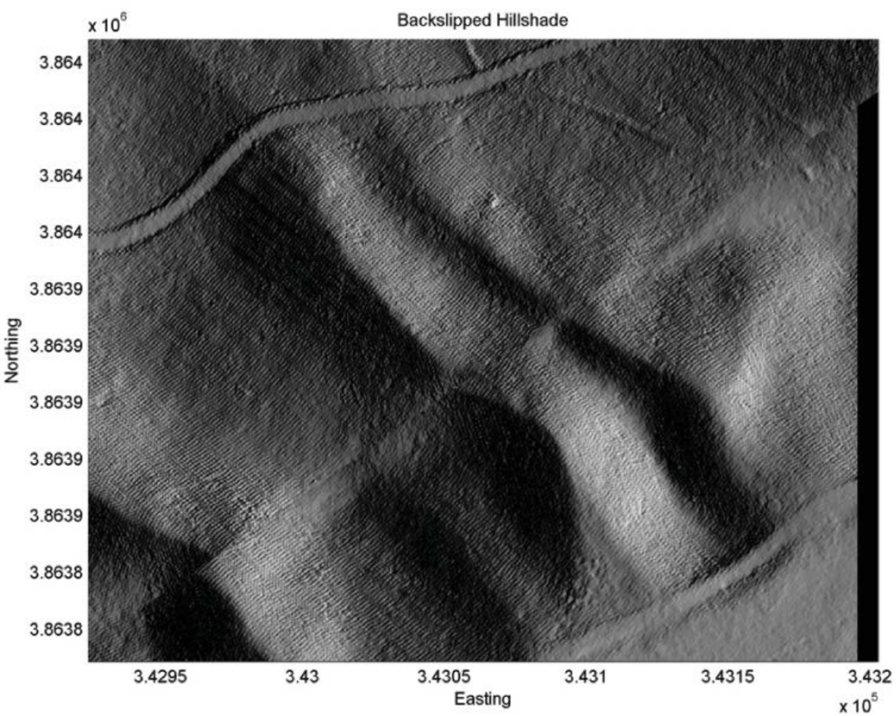


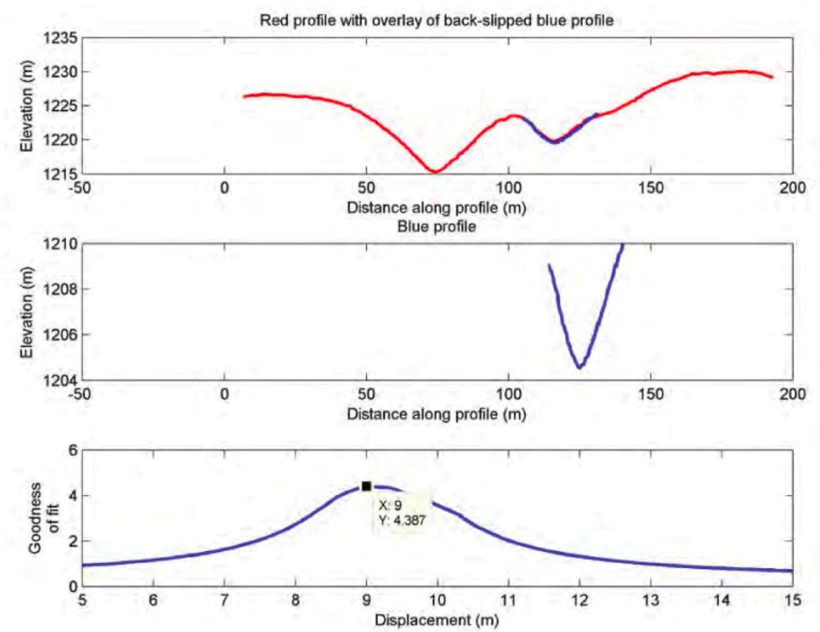
Salisbury, et al. 2013

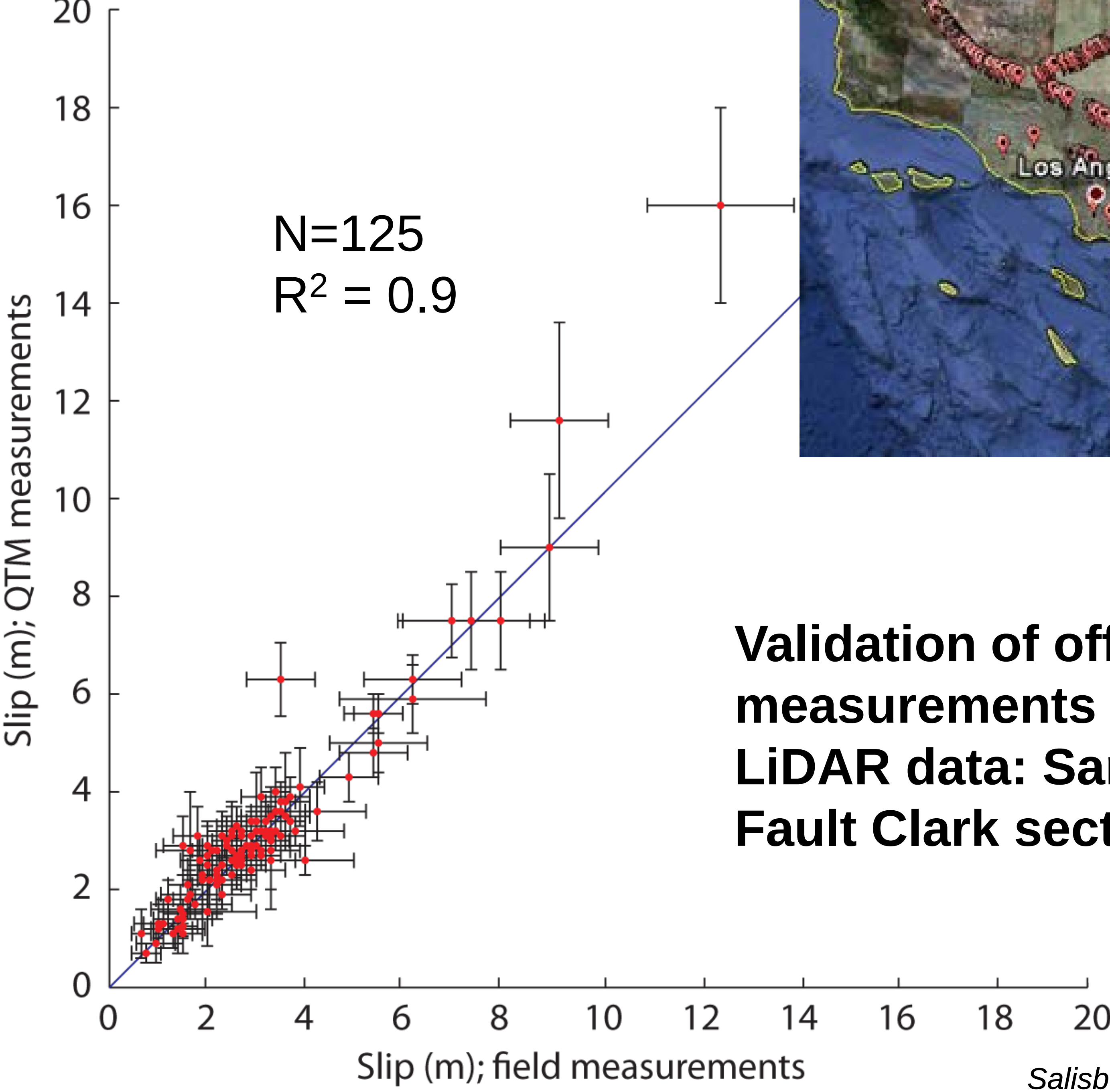

Historical Rupture
S
V
D
H
Rockwell
3-D Trenching
H
Dawson
Geomorphology
H
Salisbury
Fault-normal Trenching
S
Madden

LiDAR Measurements



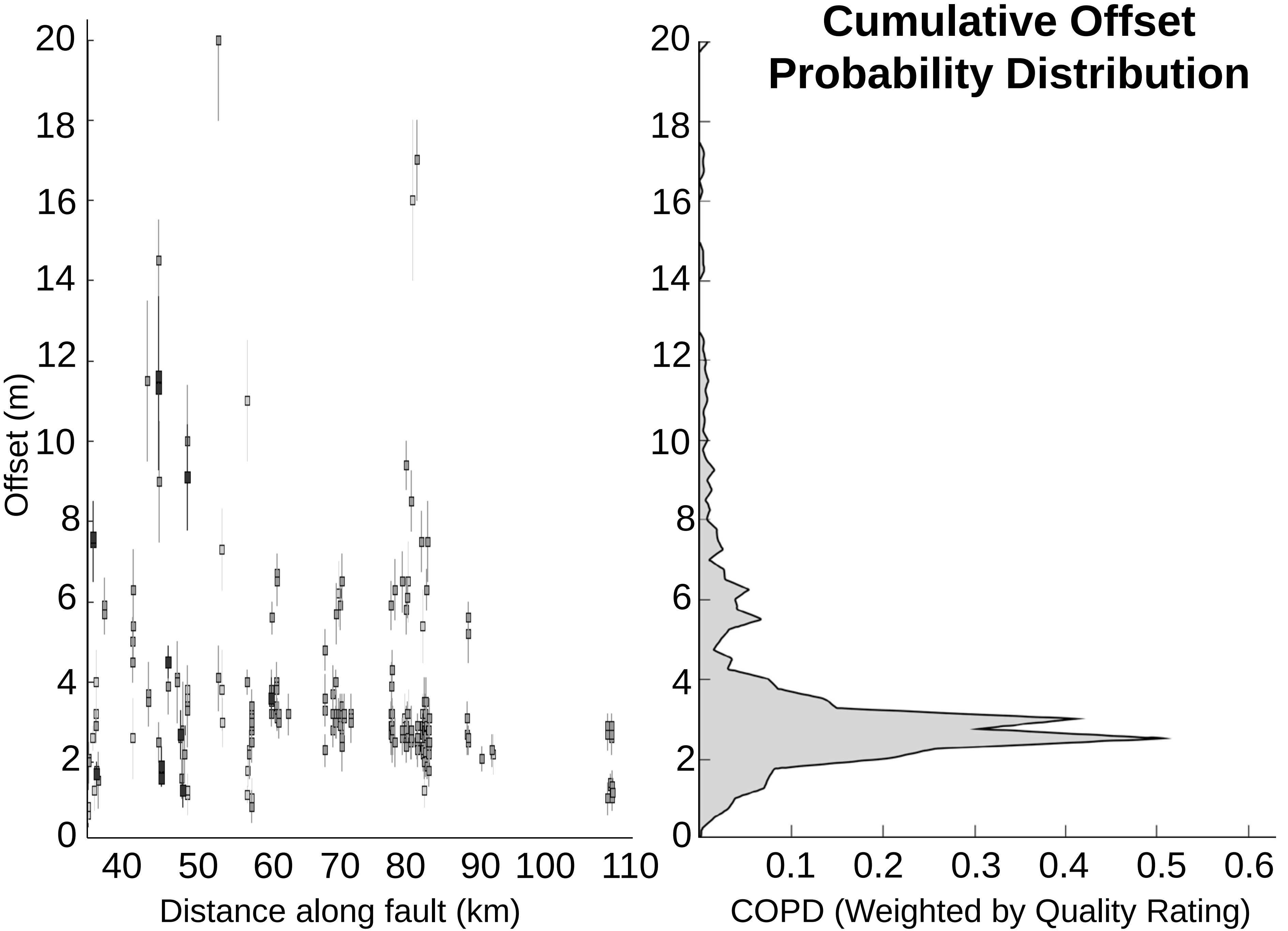


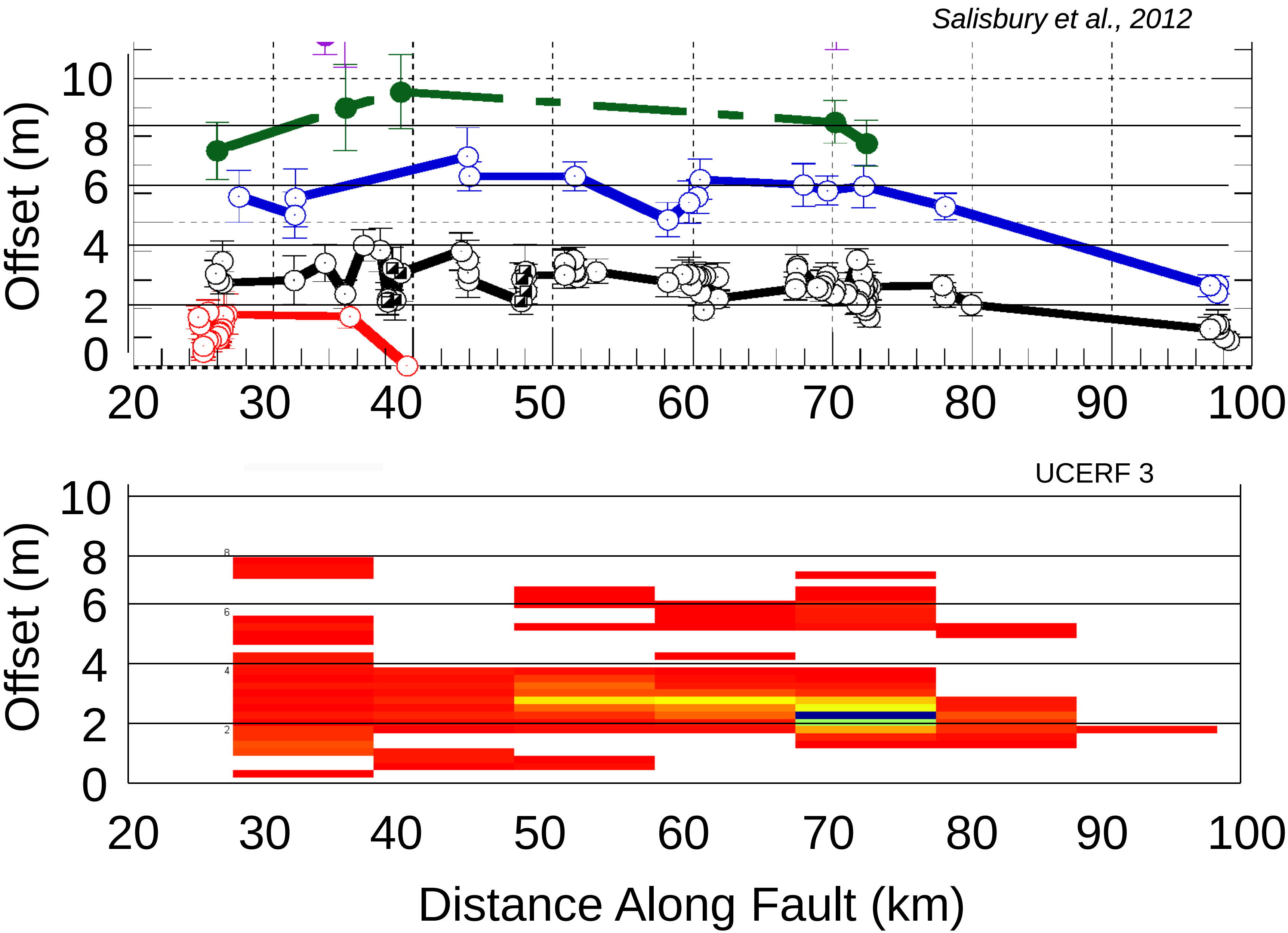


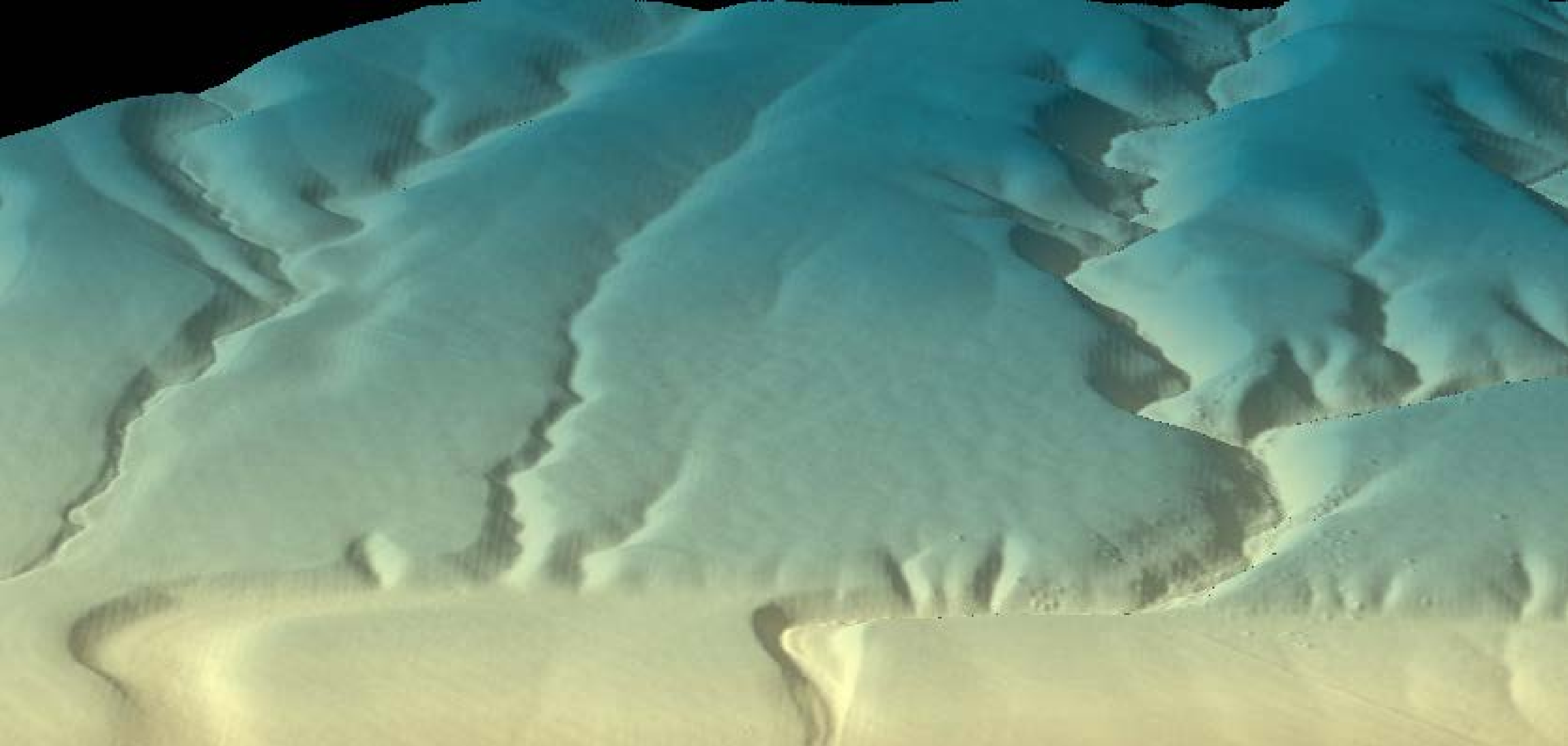


Validation of offset measurements from field and LiDAR data: San Jacinto Fault Clark section

Salisbury et al., 2012


Cumulative Offset
Probability Distribution
Offset (m)
Distance along fault (km)
COPD (Weighted by Quality Rating)
0
2
4
6
8
10
12
14
16
18
20
40
50
60
70
80
90
100
110
0.1
0.2
0.3
0.4
0.5
0.6


Salisbury et al., 2012
UCERF 3
Offset (m)
Offset (m)
0
2
4
6
8
10
20
30
40
50
60
70
80
90
100
Distance Along Fault (km)

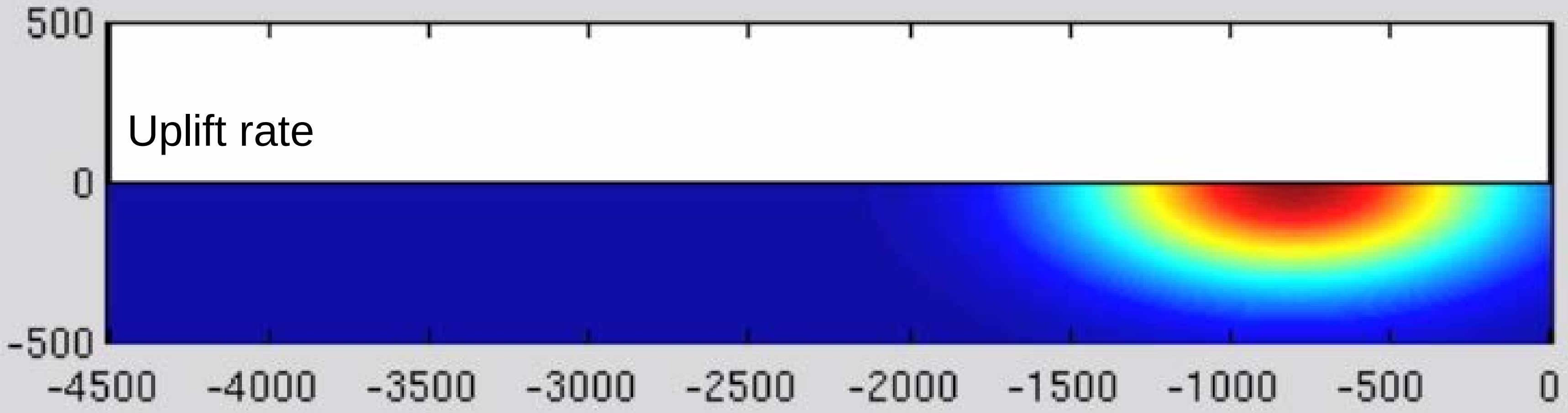


Outline

- Introduction and measuring topography
- “Seeing” at the appropriate scale
- Fault trace mapping
- Reconstructing slip history
- **Understanding geomorphic response to uplift**
- 3D topographic differencing

Background: 0.5 m Digital Elevation Model along the south-central San Andreas Fault

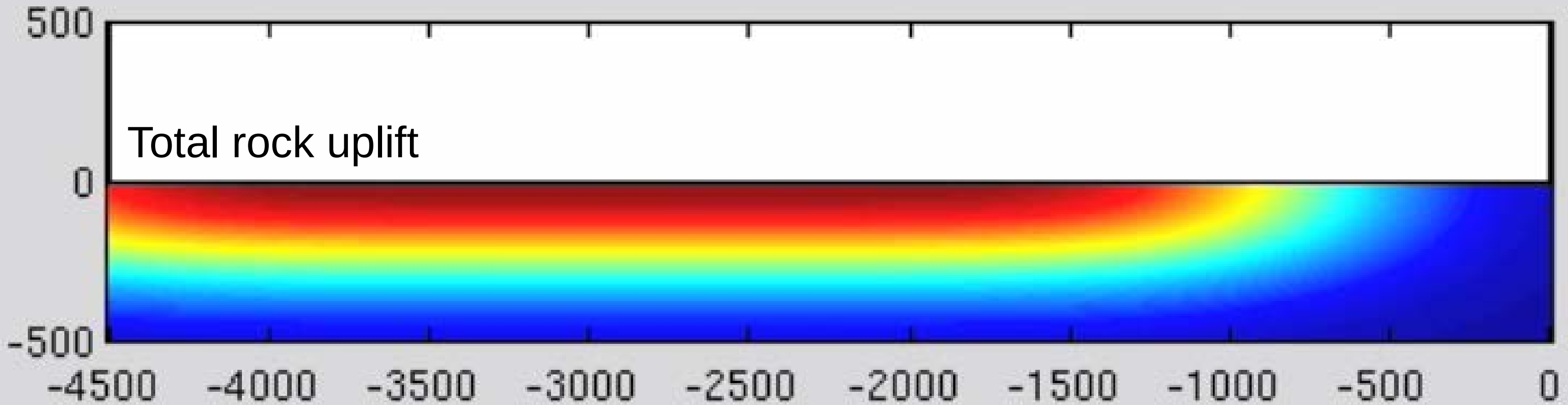
Understanding geomorphic response to uplift



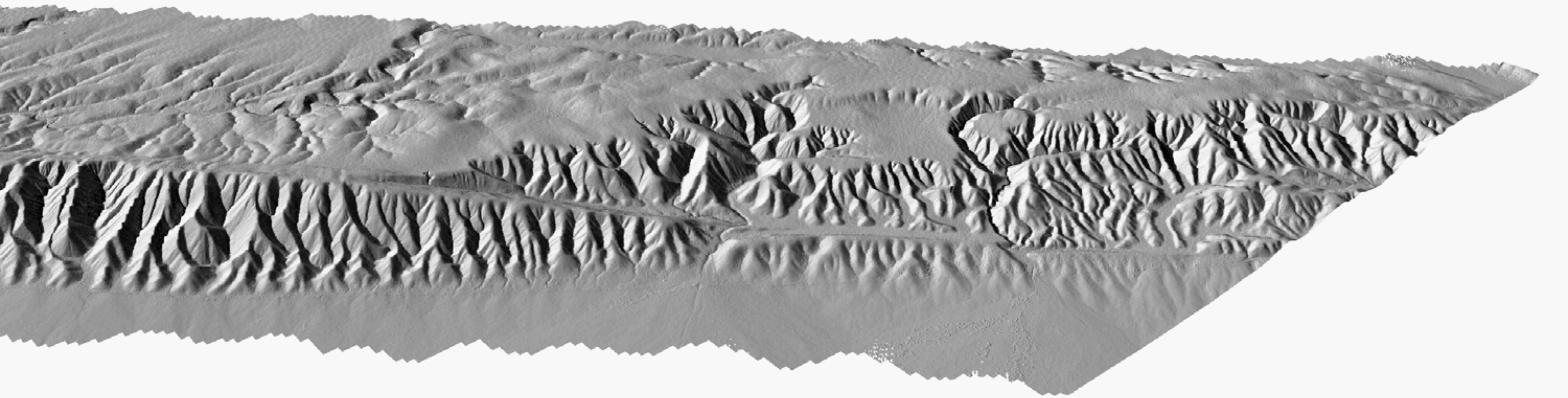
Material moves along fault though relatively stationary uplift zone:

How does landscape respond?

What will the landscape tell us about the geometry of the uplift?

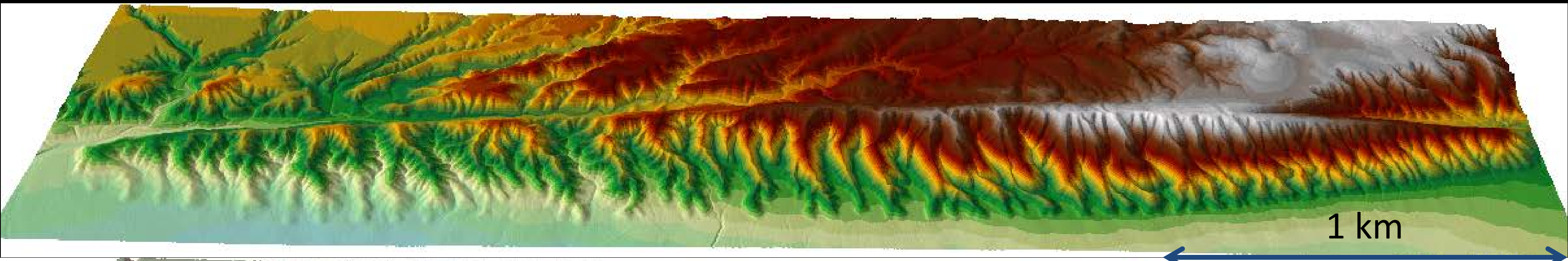


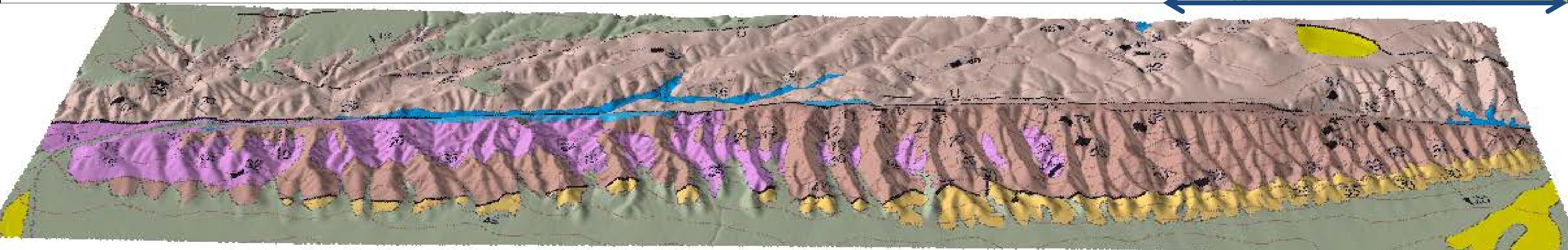
-G. E. Hilley



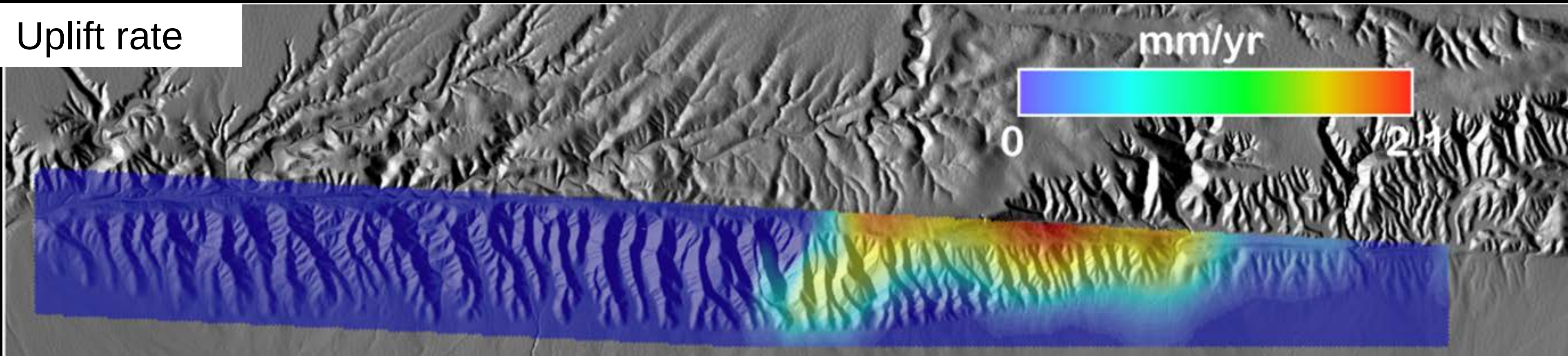
Dragon's Back Pressure Ridge, Carrizo Plain California

Arrowsmith, 1995; Hilley, 2001; Hilley and Arrowsmith, 2008

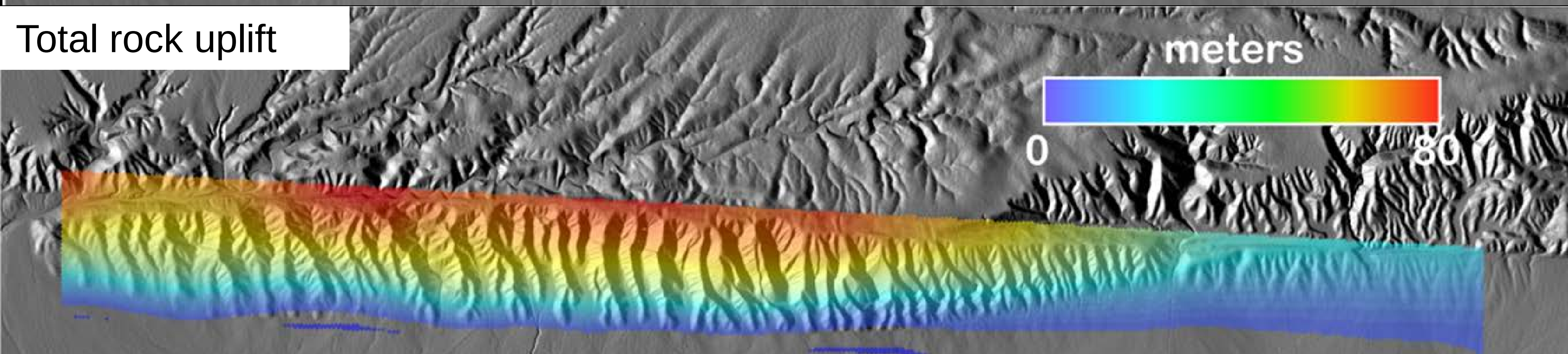




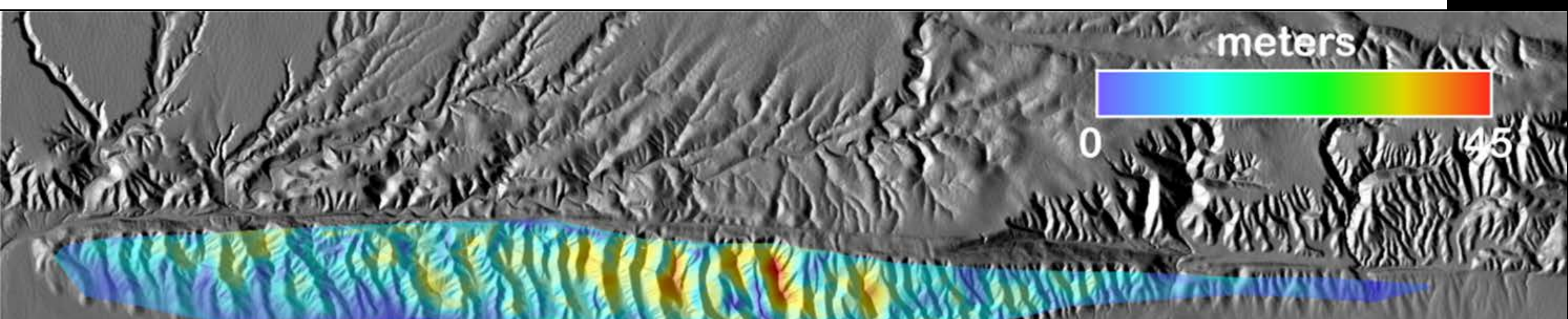
Uplift rate



Total rock uplift



Topographic metric: residual relief (ridge elevations – drainage elevation)



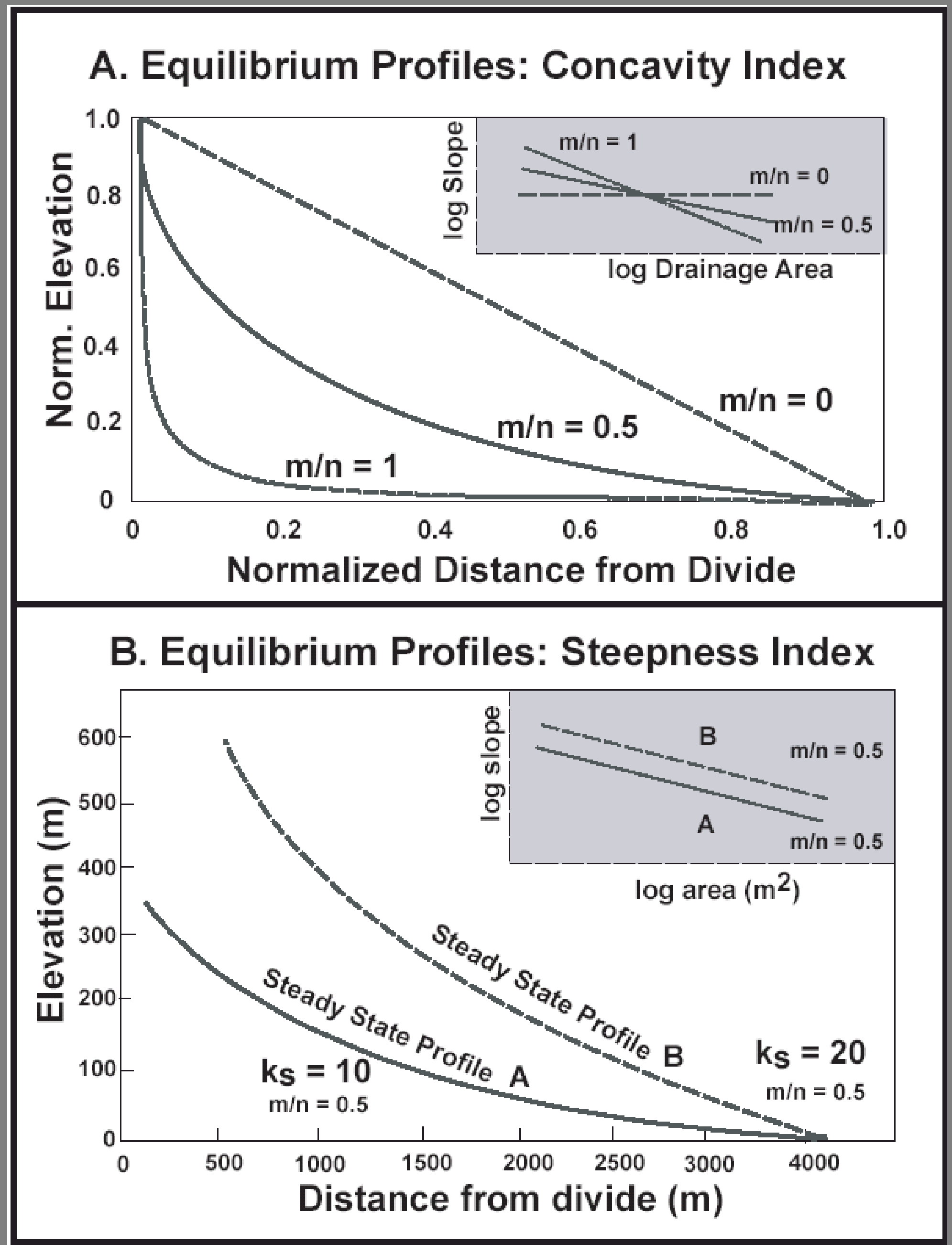
Hilley and Arrowsmith, 2008

Duvall, Kirby, and Burbank, 2004, JGR-ES

U = Rock Uplift Rate

Concavity (θ) invariant with U

Steepness (Ks) varies with U

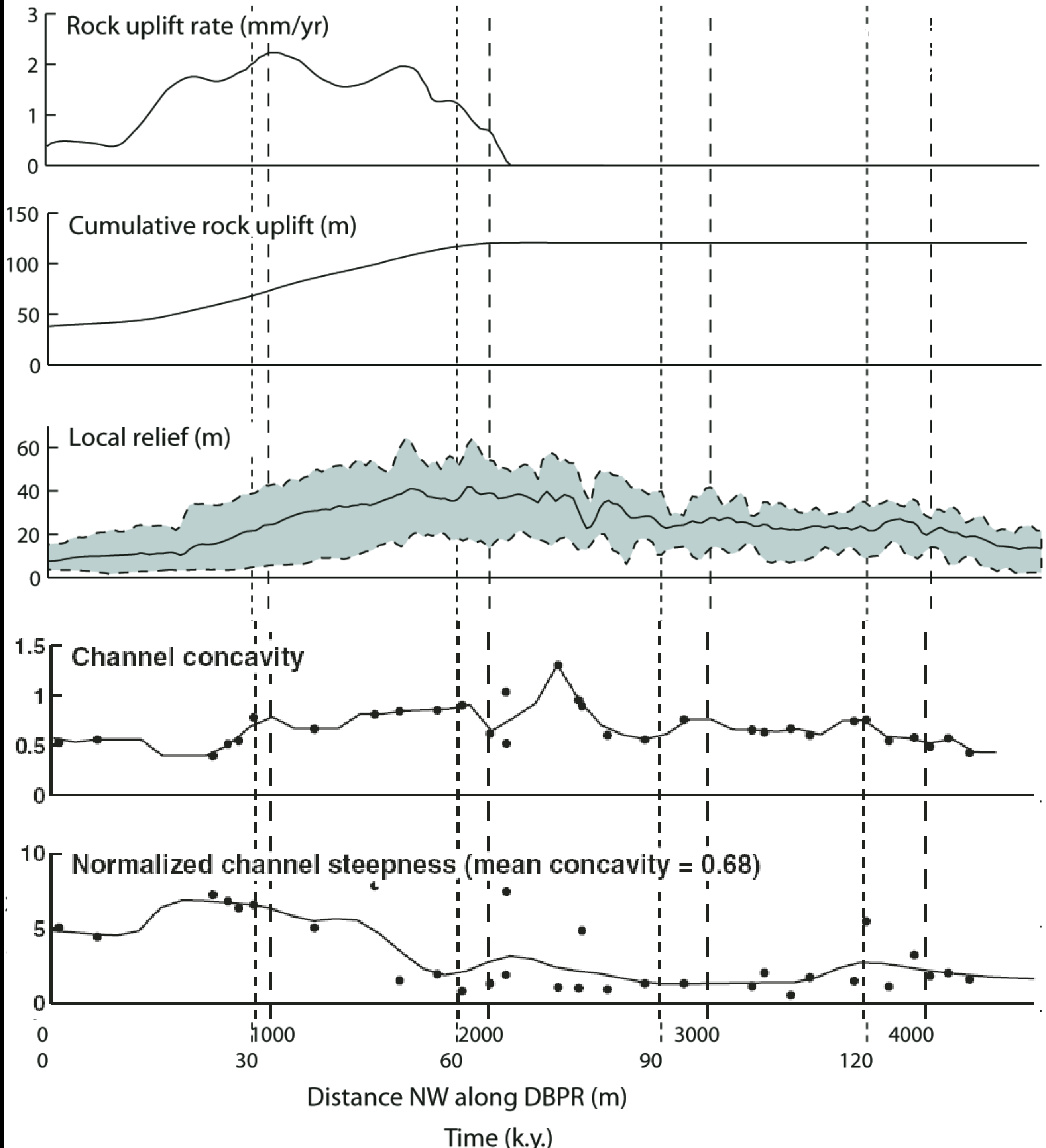


$\theta = m/n$

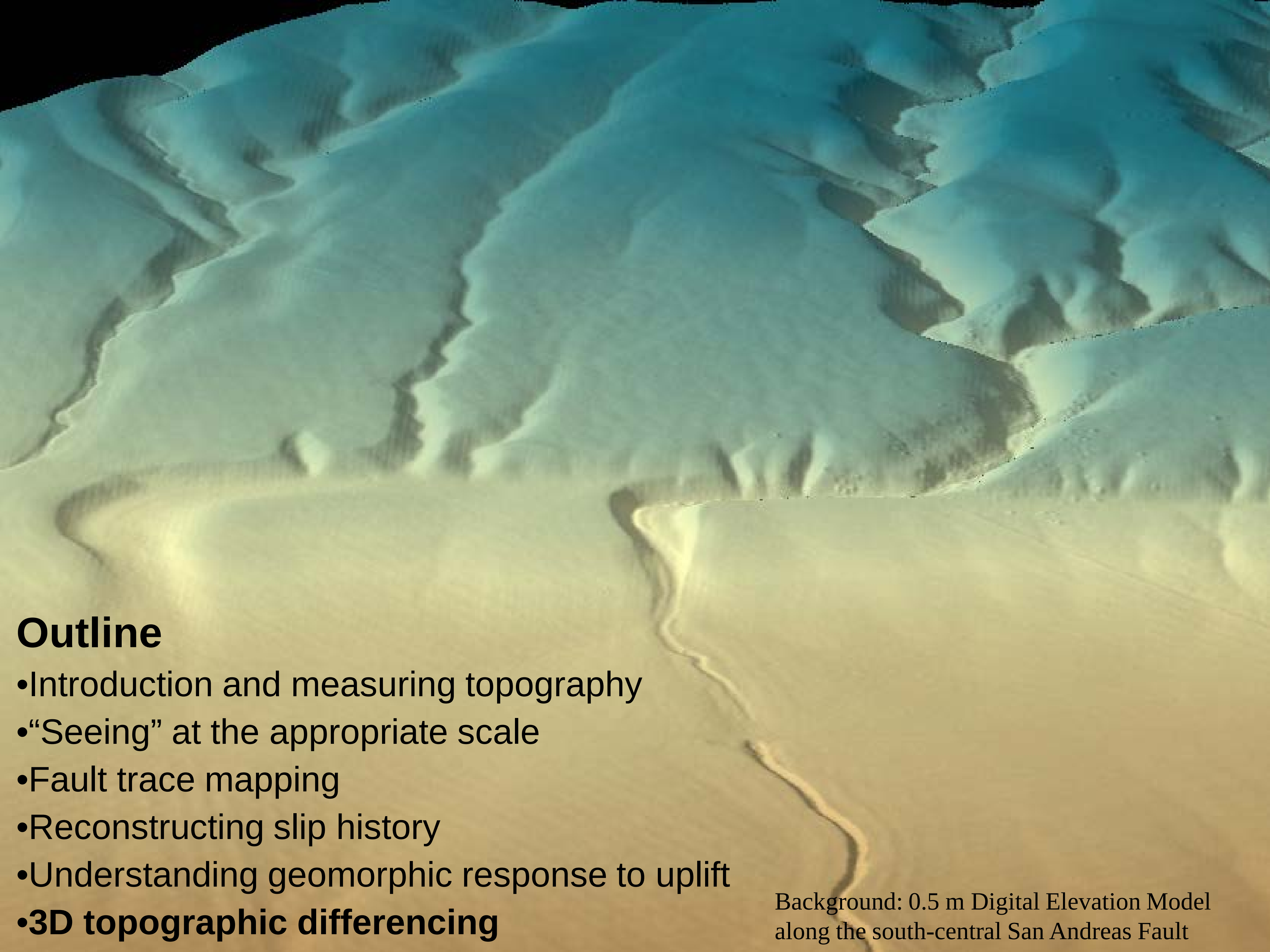
$S = k_s A^{-\theta}$

k_s

--K. X Whipple



Hilley and Arrowsmith, 2008



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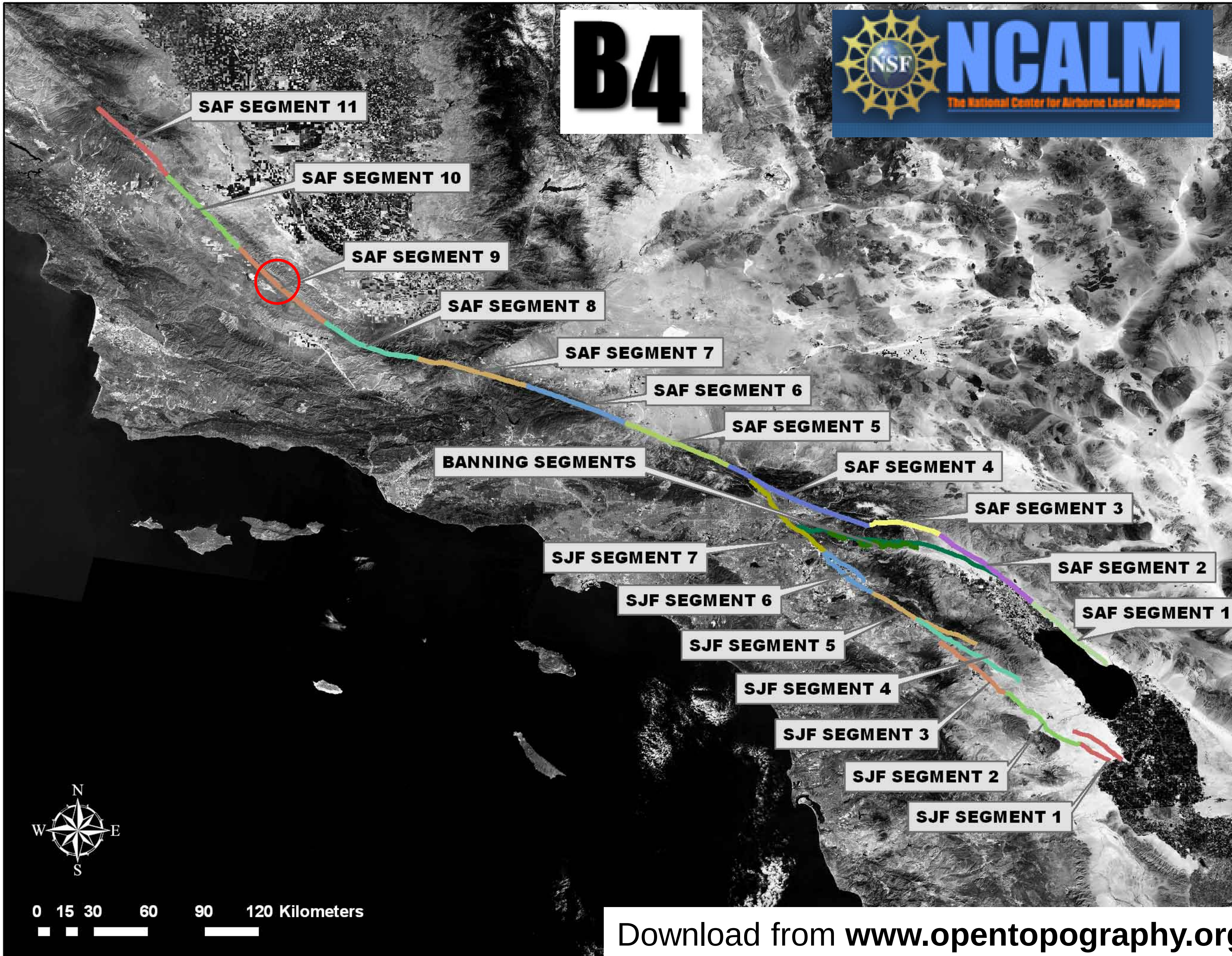
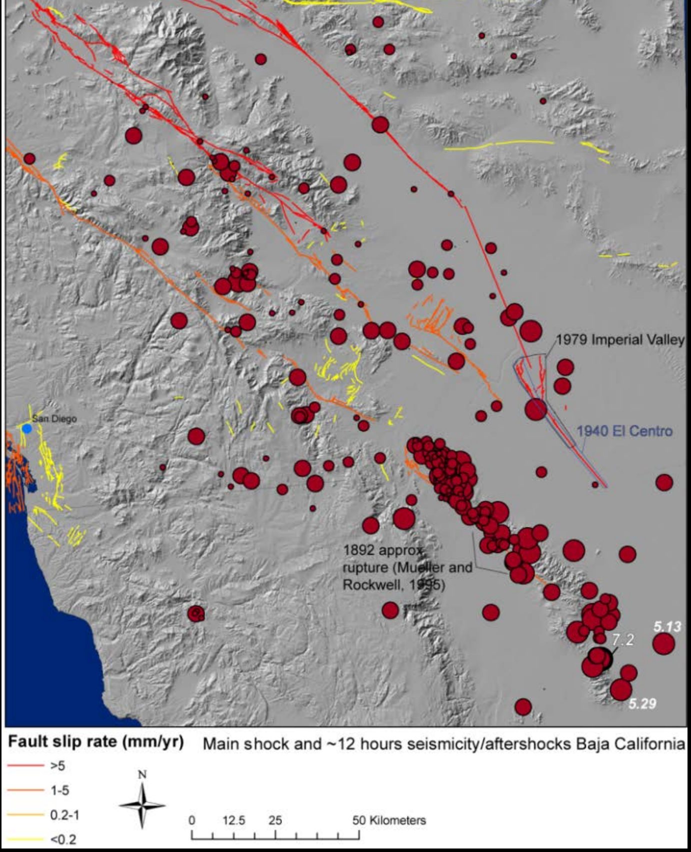
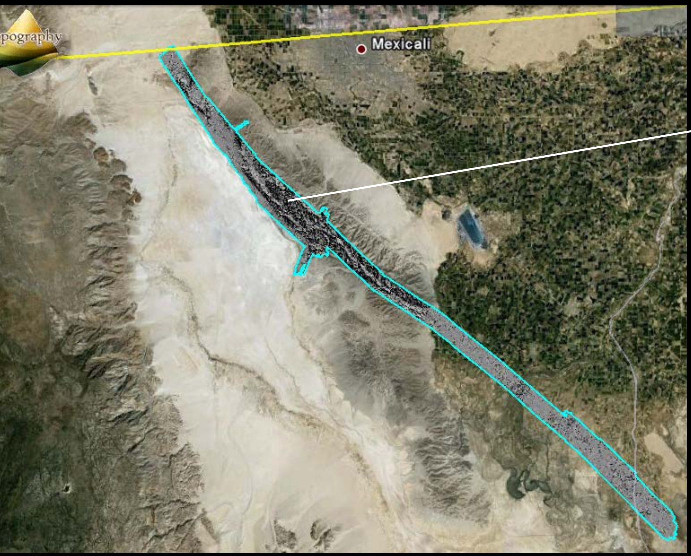


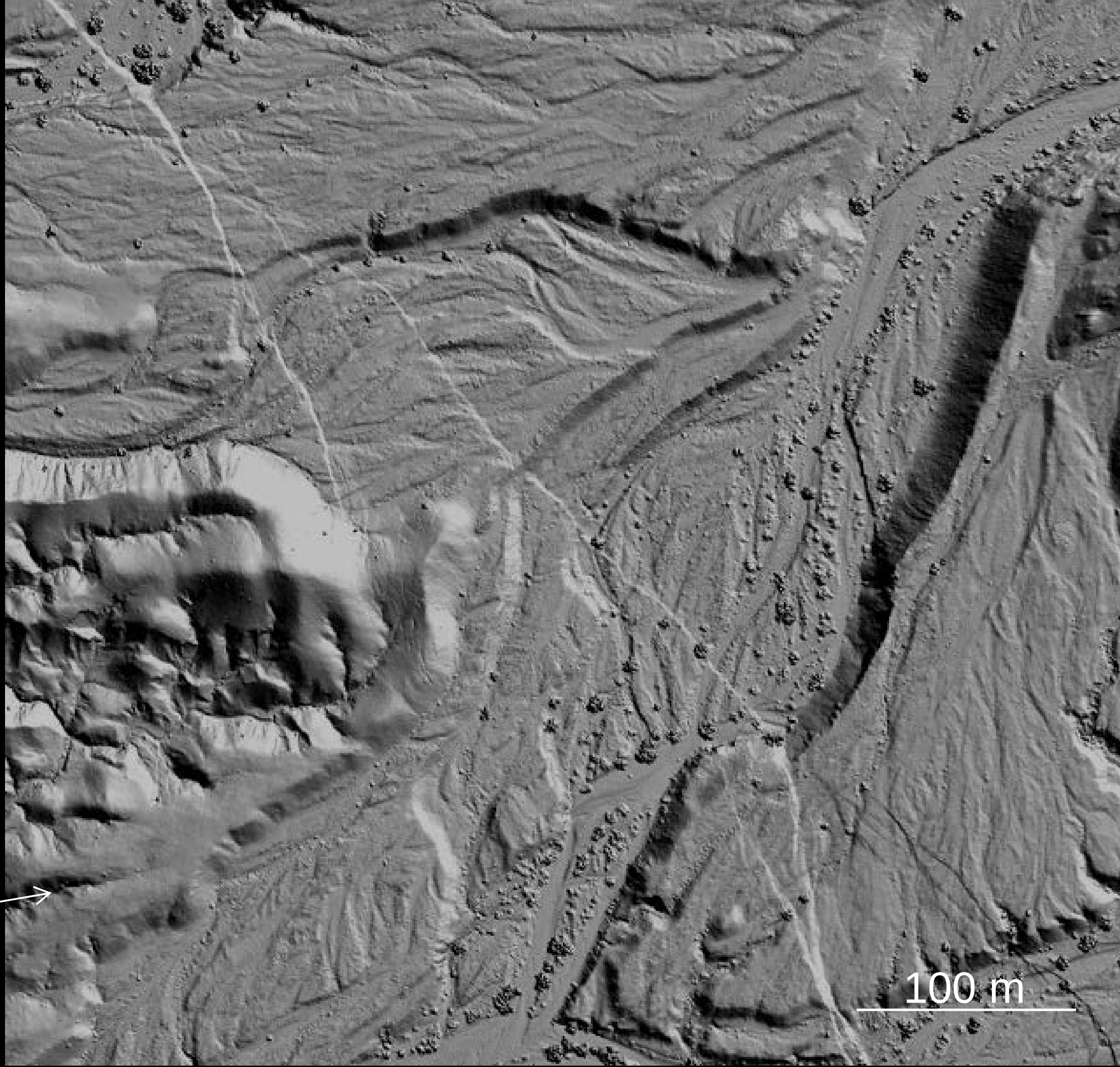
Download from www.opentopography.org

Denali 2002 earthquake rupture

Post earthquake laser scanning and repetition (B4, Hector Mine, Denali, El Mayor Cucupah)





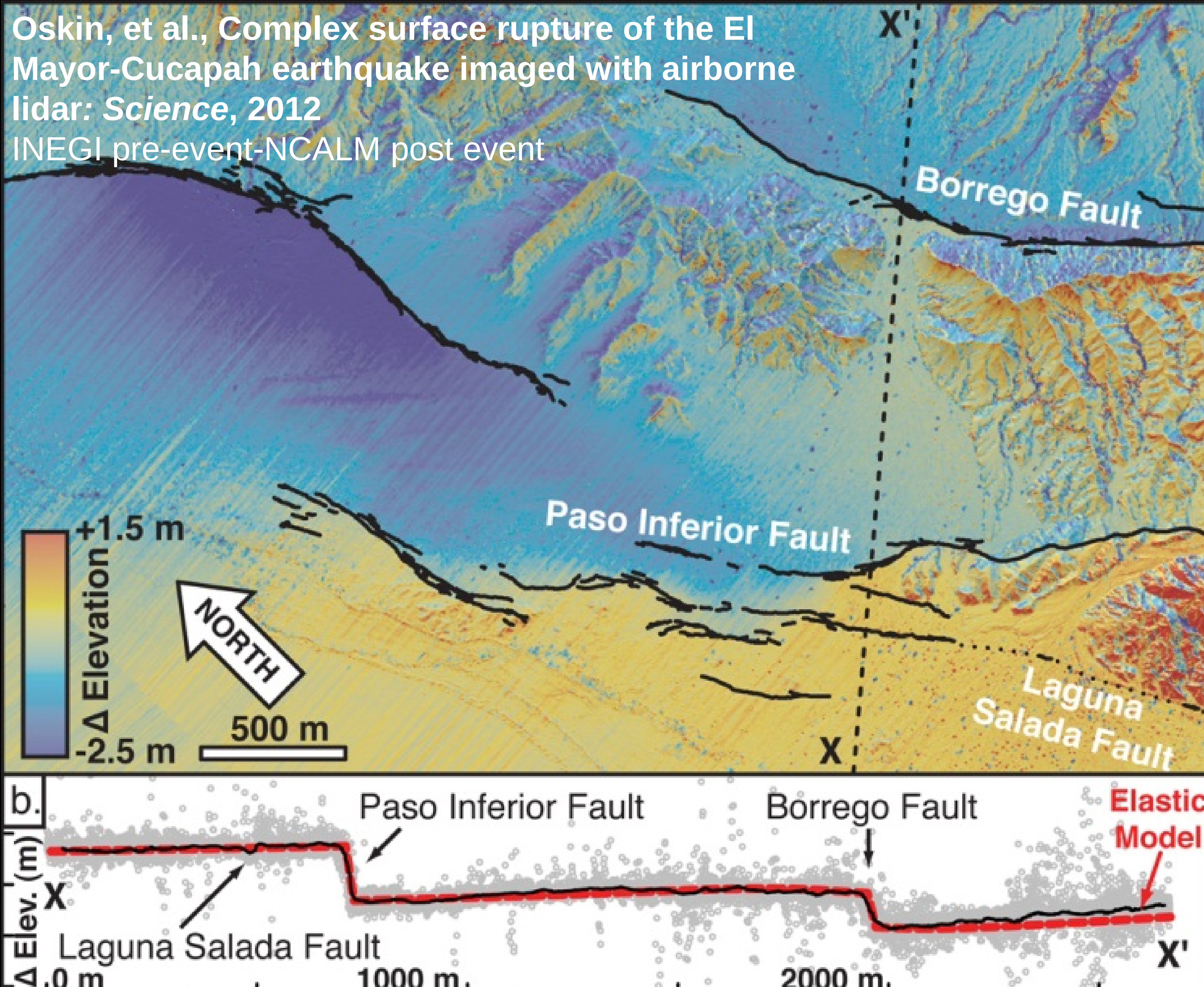


El Mayor Cucupah earthquake rupture laser scan

Oskin, et al., in review

UCDAVIS DEPARTMENT of GEOLOGY
CICESE
ASU School of Earth & Space Exploration ARIZONA STATE UNIVERSITY
NCALM


Photo by Tom Rockwell

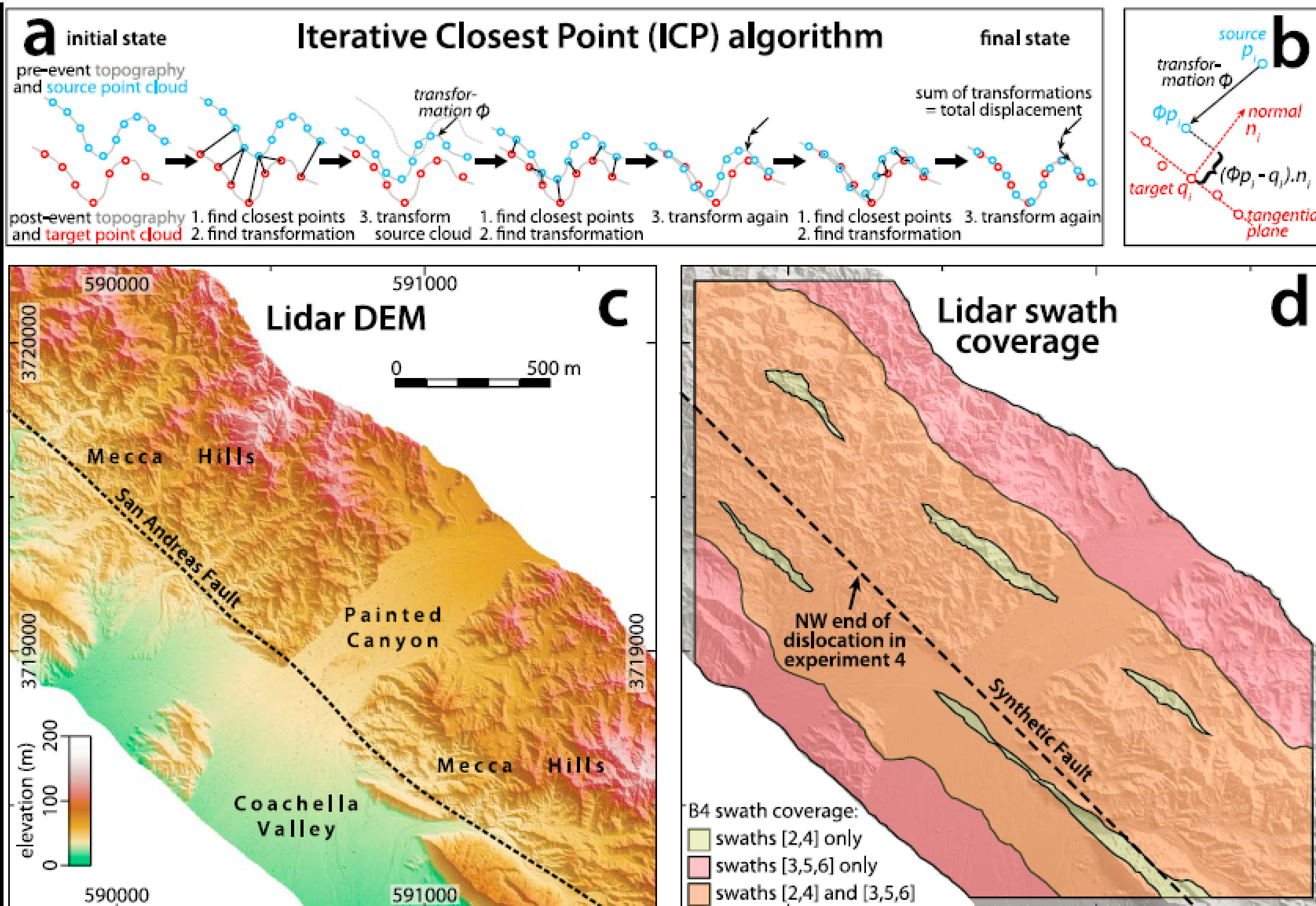


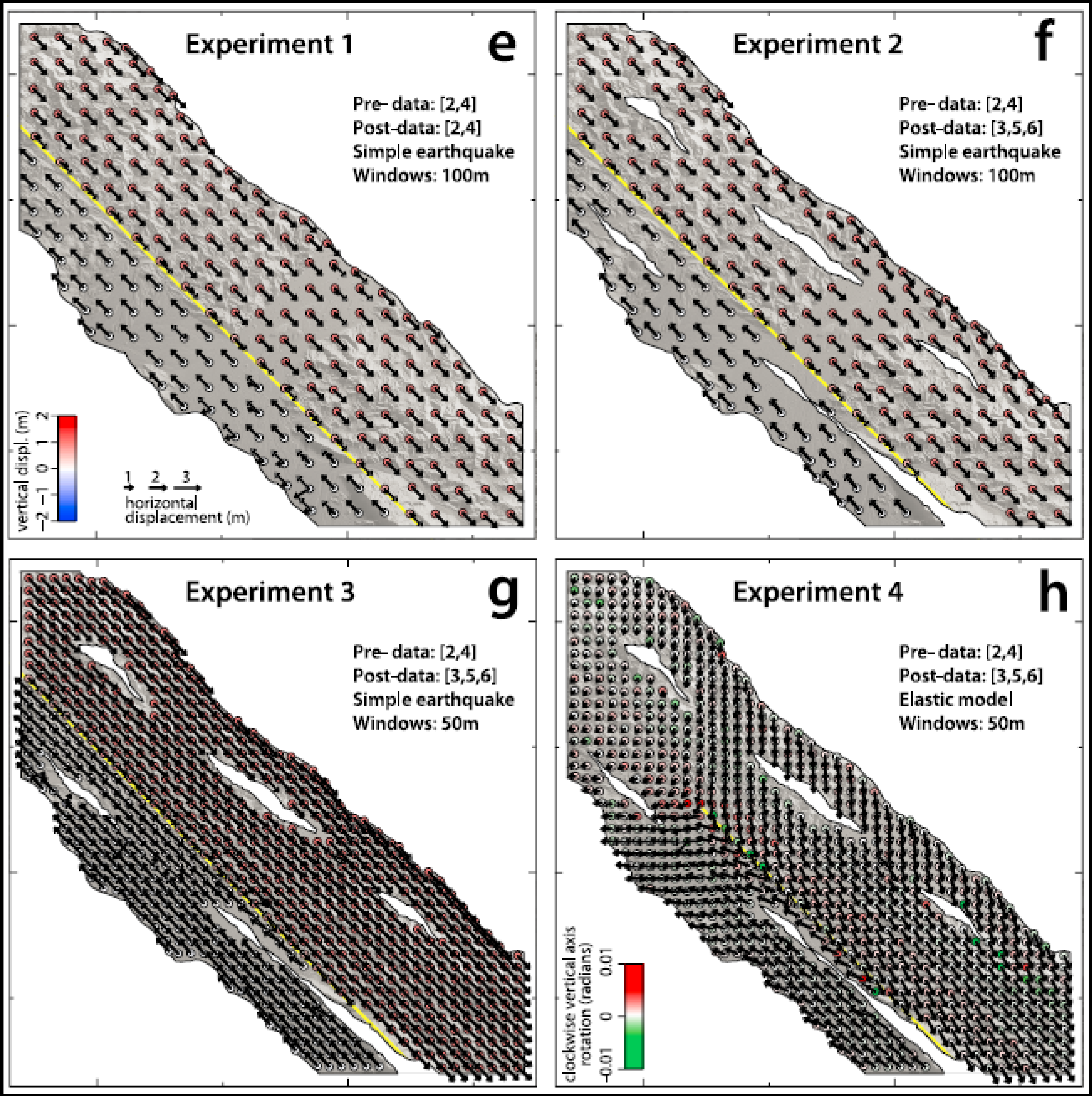
Oskin, et al., Complex surface rupture of the El Mayor-Cucapah earthquake imaged with airborne lidar: Science, 2012
INEGI pre-event-NCALM post event
X'
Borrego Fault
Paso Inferior Fault
Laguna Salada Fault
X
+1.5 m
Δ Elevation
-2.5 m
NORTH
500 m
b.
Paso Inferior Fault
Borrego Fault
Elastic Model
Δ Elev. (m)
X
Laguna Salada Fault
X'
0 m
1000 m
2000 m

Three-dimensional surface displacements and rotations from differencing pre- and post-earthquake LiDAR point clouds

GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L16301, doi:10.1029/2012GL052460, 2012

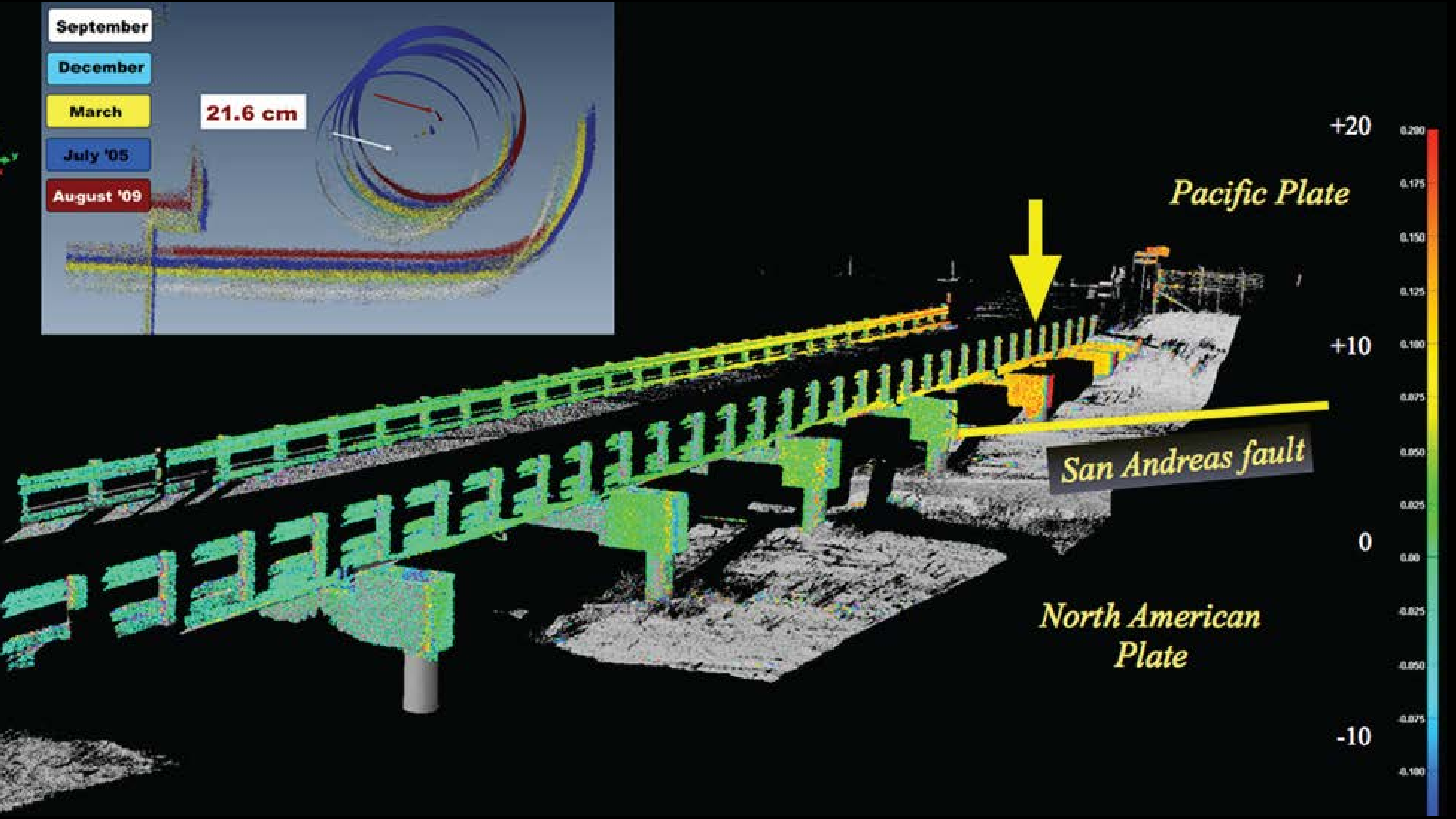
Edwin Nissen,[1,2] Aravindhan K. Krishnan,[1] J. Ramón Arrowsmith,[1] and Srikanth Saripalli[1]





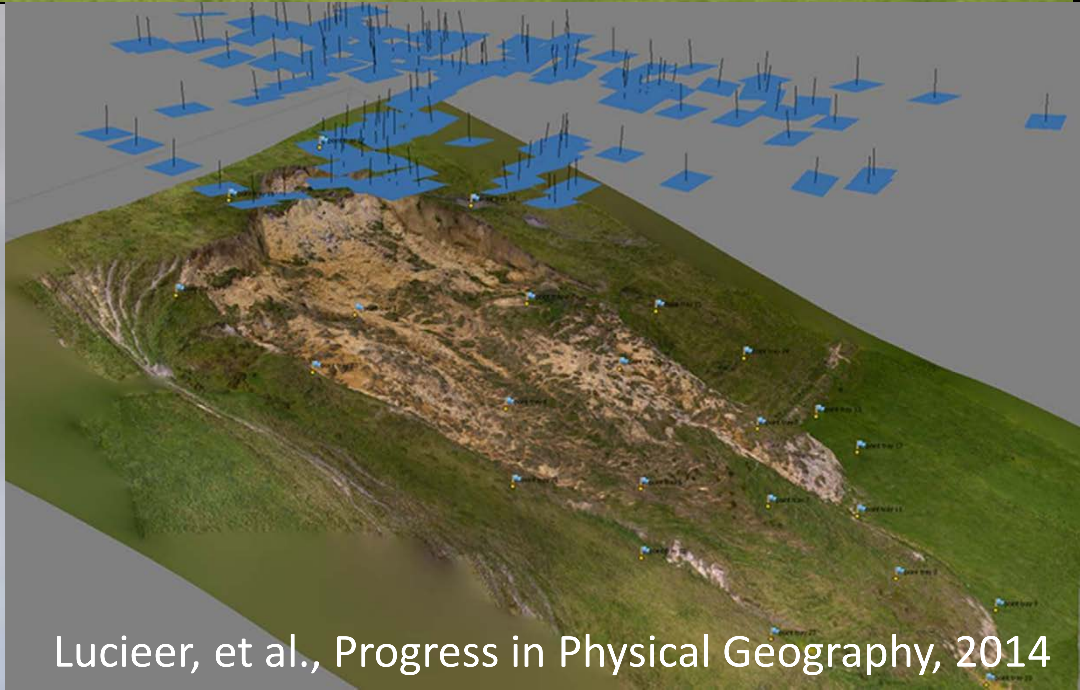
Experiment 1
e
Pre- data: [2,4]
Post-data: [2,4]
Simple earthquake
Windows: 100m
vertical displ. (m)
−2 −1 0 1 2
1 2 3
horizontal
displacement (m)
Experiment 2
f
Pre- data: [2,4]
Post-data: [3,5,6]
Simple earthquake
Windows: 100m
Experiment 3
g
Pre- data: [2,4]
Post-data: [3,5,6]
Simple earthquake
Windows: 50m
Experiment 4
h
Pre- data: [2,4]
Post-data: [3,5,6]
Elastic model
Windows: 50m
clockwise vertical axis
rotation (radians)
−0.01 0 0.01

Repeat terrestrial laser scanning of the bridge at Parkfield: colors show relative motion across the slipping San Andreas Fault (cm)

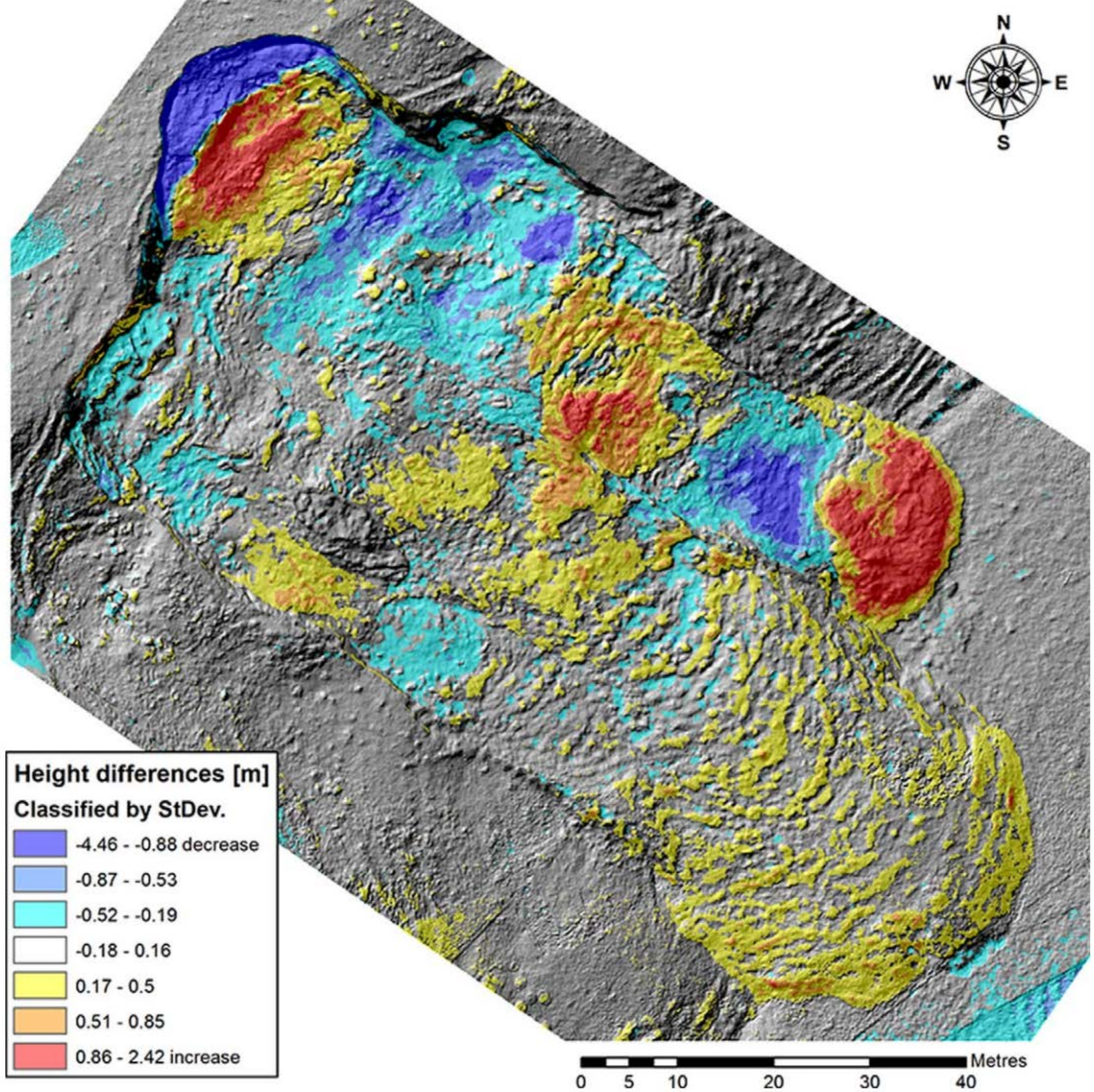


TLS data and image from G. Bawden (USGS). AGU Bowie Lecture and Grand Challenges in Geodesy

Home Hill landslide in southern Tasmania—displacements from repeat SfM

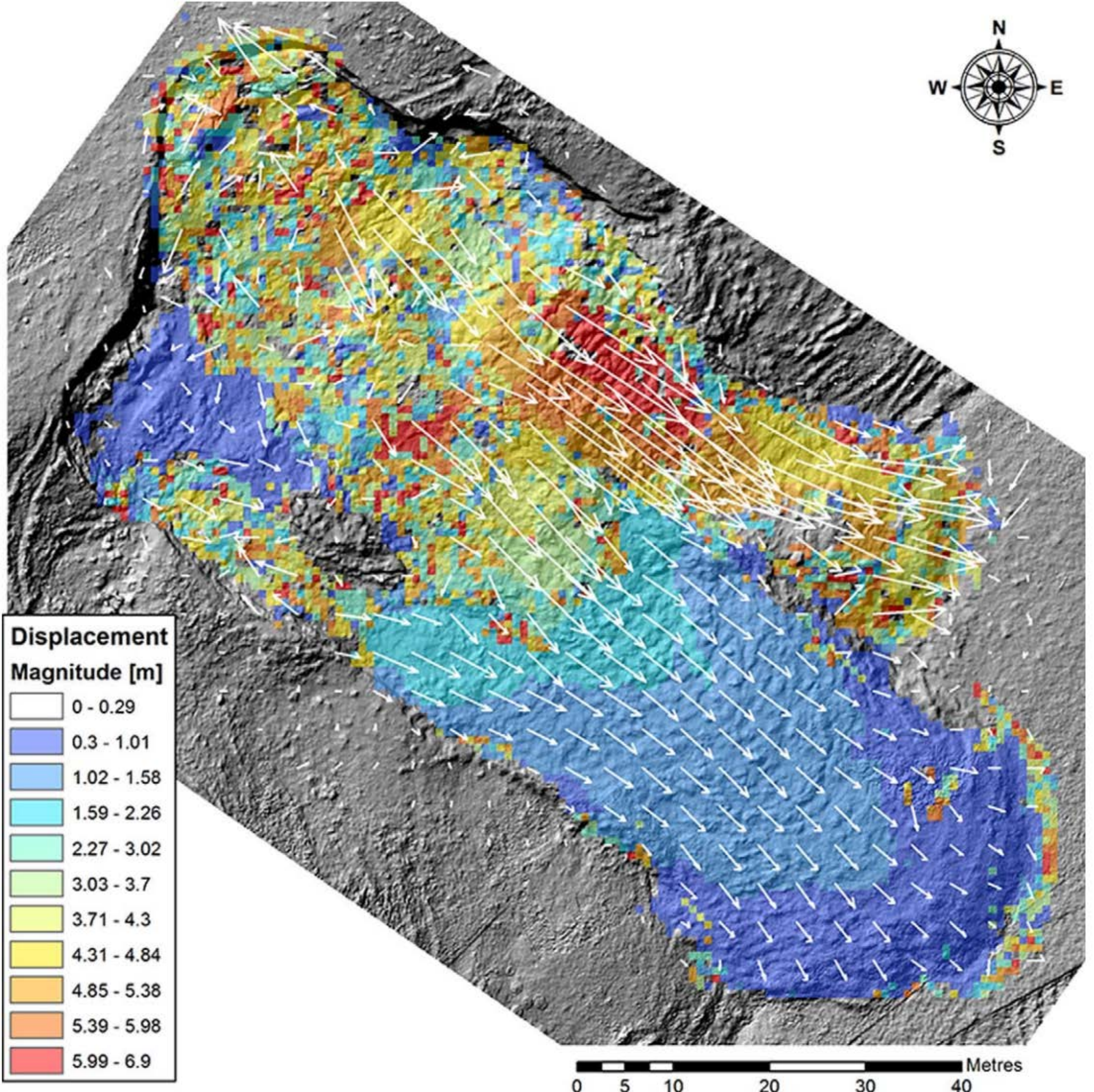


Lucieer, et al., Progress in Physical Geography, 2014



Difference between the 1 cm DEMs of 19 July 2011 and 10 November 2011

Lucieer, et al., Progress in Physical Geography, 2014



Displacement of the Home Hill landslide between 19 July 2011 and 10 November 2011 using the COSI-Corr algorithm (Leprince, et al., 2007)

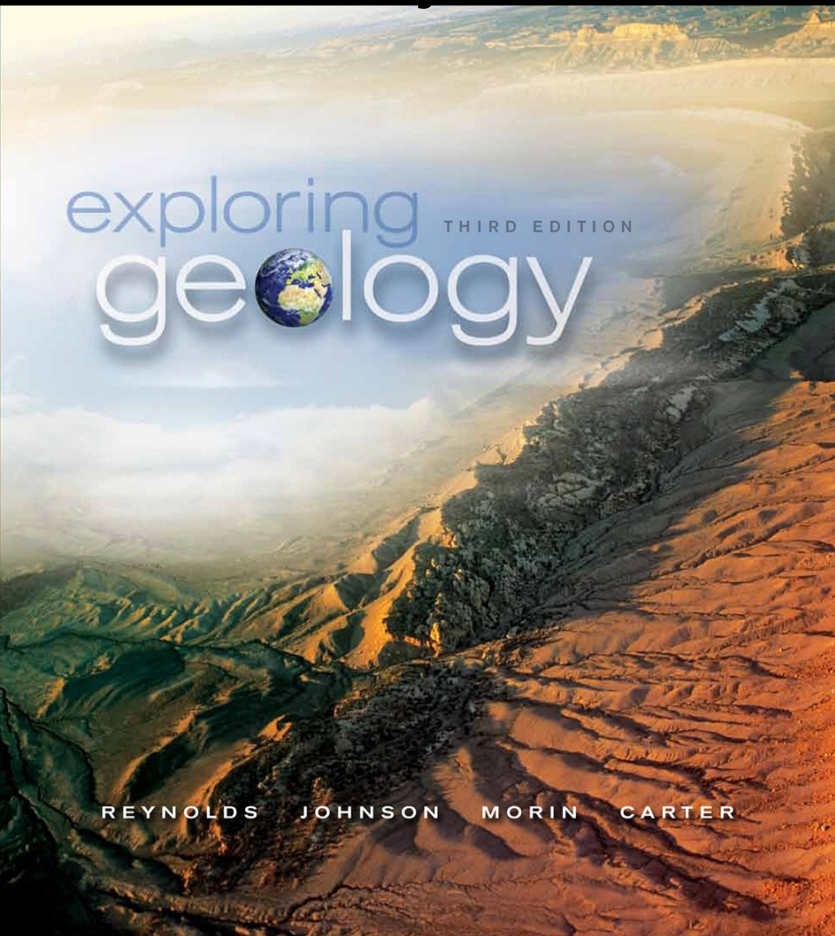
Lucieer, et al., Progress in Physical Geography, 2014

Summary

- LiDAR provides dm to cm global accurate measure of the earth's surface
- Meter scale is critical for structural and geomorphic processes
- Main applications in faulting-related investigations can be separated into fault zone mapping, reconstructing offsets, investigating geomorphic responses to active deformation, and differencing of repeat surveys

Looking ahead

- Lots more data and problems out there!
- 4 dimensions: directly measuring the displacements
- Processing and filtering enhancements: looking for the signal in all the data (e.g., Hilley, et al., 2010; Delong, et al., 2010)
- Bring these data and their depiction of the earth's geomorphic and tectonic processes to geoscience education

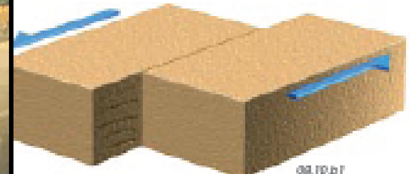


Chapter 8

Image Number: 08.00.a3: © Duncan Heron; 08.01.mtb1: Spokane Research Lab/NIOSH/CDC; Courtesy of J.M. Logan and F.M. Chester, Center for Tectonophysics, Texas A&M University; 08.02.mtb1: Spokane Research Lab/NIOSH/CDC; 08.03.c6: © Dean Conger/Corbis; 08.10.c2: Ohio State University, USGS, National Center for Airborne Laser Mapping, OpenTopography, and J Ramon Arrowsmith, Arizona State University; 08.11.a9: © Dr. Marli Miller/Visuals Unlimited;

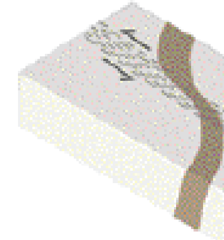
B Where Do Strike-Slip Faults and Shear Zones Form?

During strike-slip movement, one block of rock is sheared sideways past another block of rock. This can various settings, including transform plate boundaries and within the interiors of plates.


08.10.b1

Shear stresses can be imposed on rocks horizontally, vertically, or at some intermediate angle. When the shear stresses are horizontal (▲), they act to shear the two sides of a block in opposite horizontal directions. As a result of the stresses, shearing moves rocks horizontally past one another. Shearing in the upper parts of the crust occurs along a fault, as shown here, and is accompanied by fracturing of adjacent rocks. Shearing at depth will occur along a zone of ductile deformation and will be accompanied by metamorphism and the formation of foliation and lineation.

Stresses can form a strike-slip zone that functions as a plate boundary or that is totally within a tectonic plate (▶). A strike-slip zone may offset the rocks hundreds of kilometers or less than a meter. A strike-slip fault with relatively small amounts of displacement is typically a single fault or several adjacent faults, but zones with larger displacements are thick zones of shear (shear zones).


08.10.b2

08.10.b3

◀ All transform boundaries are faults that accommodate the la placement of one plate past a Most are a boundary betwee oceanic plates, as are the o here by small white arrows, transform fault can also se two continental plates or separate an oceanic pla a continental one.

C What Features Form Along Strike-Slip Faults?

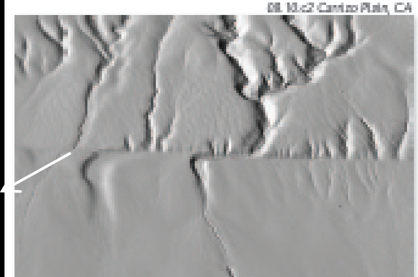
Strike-slip faults result in a number of distinctive features, including offset streams. They also can have fe formed where one block of rock shears past another or where rocks are forced around a bend in the fau

Strike-slip faults displace rocks on either side horizontally relative to one another, so in a simple case would not uplift or downdrop either side. However, many strike-slip faults have bends, where the fault changes its trace across the land surface from one orientation to another. Right-lateral motion on the fault shown here causes compression along the bend, forming ridges and troughs that are the surface expression of folds and thrust faults.


08.10.c1

Horizontal displacement surface features, includi agricultural fields, and s beds. Over time, offse develop a characteri where they jog para fault, before contin their prefaulting c direction of the j the direction of movement acro

08.10.c2 Carrizo Plain, CA



◀ Faults that are currently active can offset streams, ridges, and other topographic features. The San Andreas fault in central California is the linear feature cutting across drainages in the center of this computer-generated view (looking east). The large offset stream takes a jog as it crosses the fault. Is this fault a left-lateral or right-lateral strike-slip fault? Hint: Imagine you are standing in the streambed on the near side of the fault, and then observe which way the streambed on the opposite side has been displaced relative to you.

Before You Leave This Be Able To

- ✓ Describe or sketch how def and metamorphism occur in continental rifts, rifted conti margins, and mid-ocean rid
- ✓ Describe strike-slip faults, s settings where they occur, a features formed on the land