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

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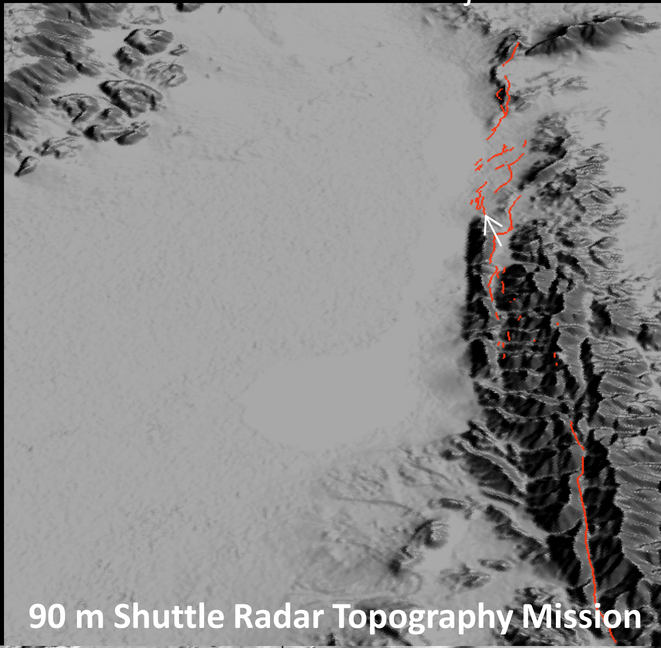
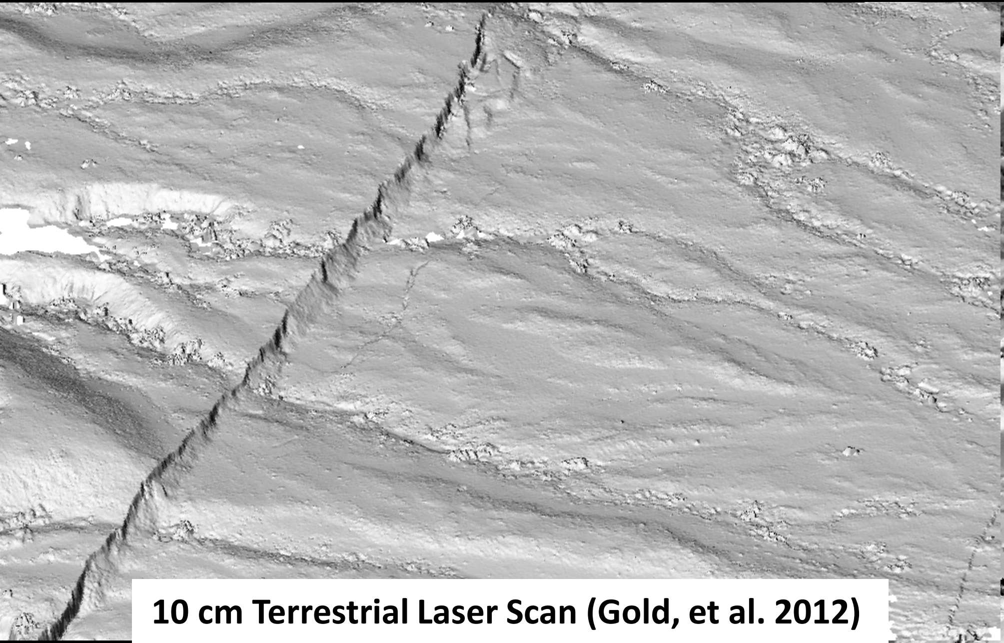
Data and processing: B4, NCALM, OpenTopography
Supported by NSF, USGS, SCEC, NASA

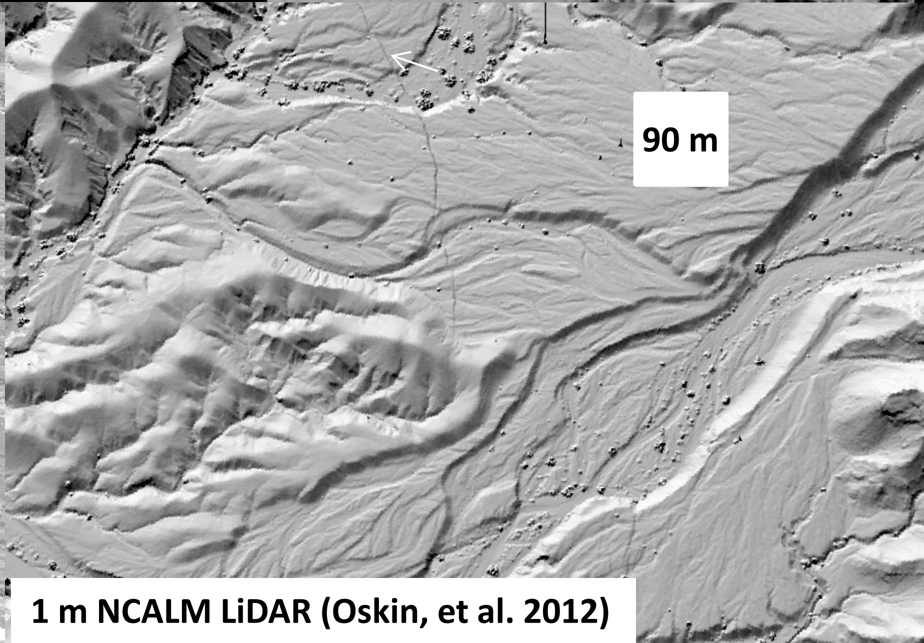
2010 El Mayor Cucupah earthquake, Baja California



90 m Shuttle Radar Topography Mission

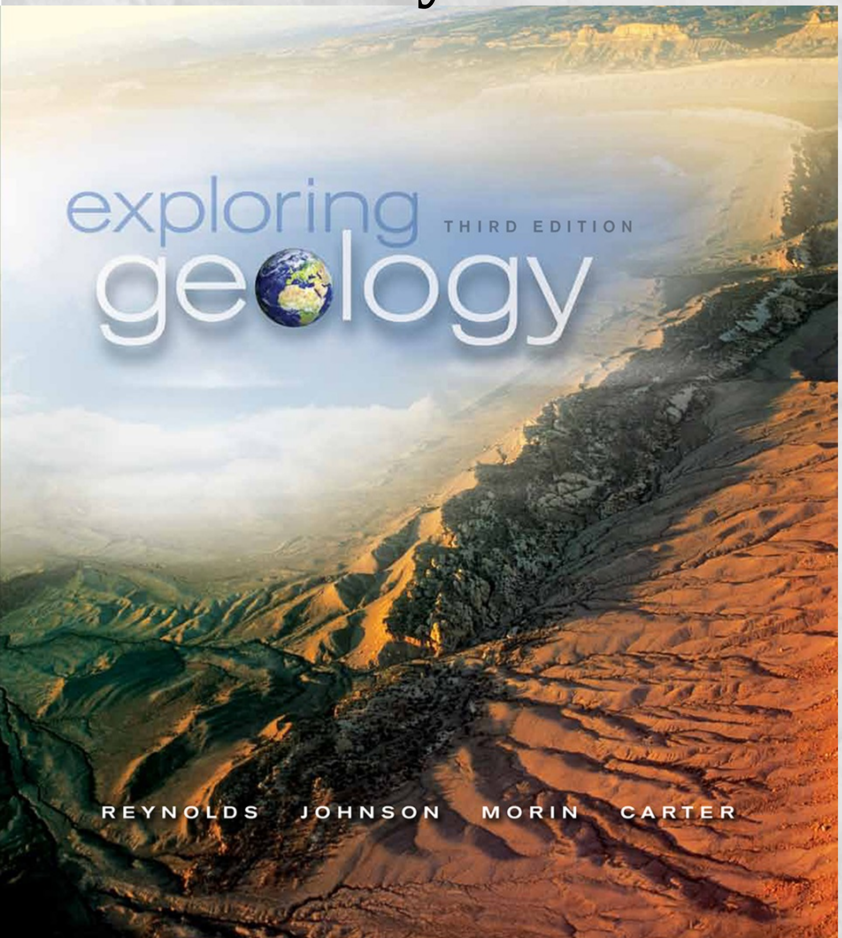


10 cm Terrestrial Laser Scan (Gold, et al. 2012)



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

Getting Lidar into introductory textbooks!



Deformation and Metamorphi

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

AFRICA
SOUTH AMERICA
South Atlantic Ocean
Plate Boundary

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.

Horizontal displacement
surface features, includi
agricultural fields, and
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.c1

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.

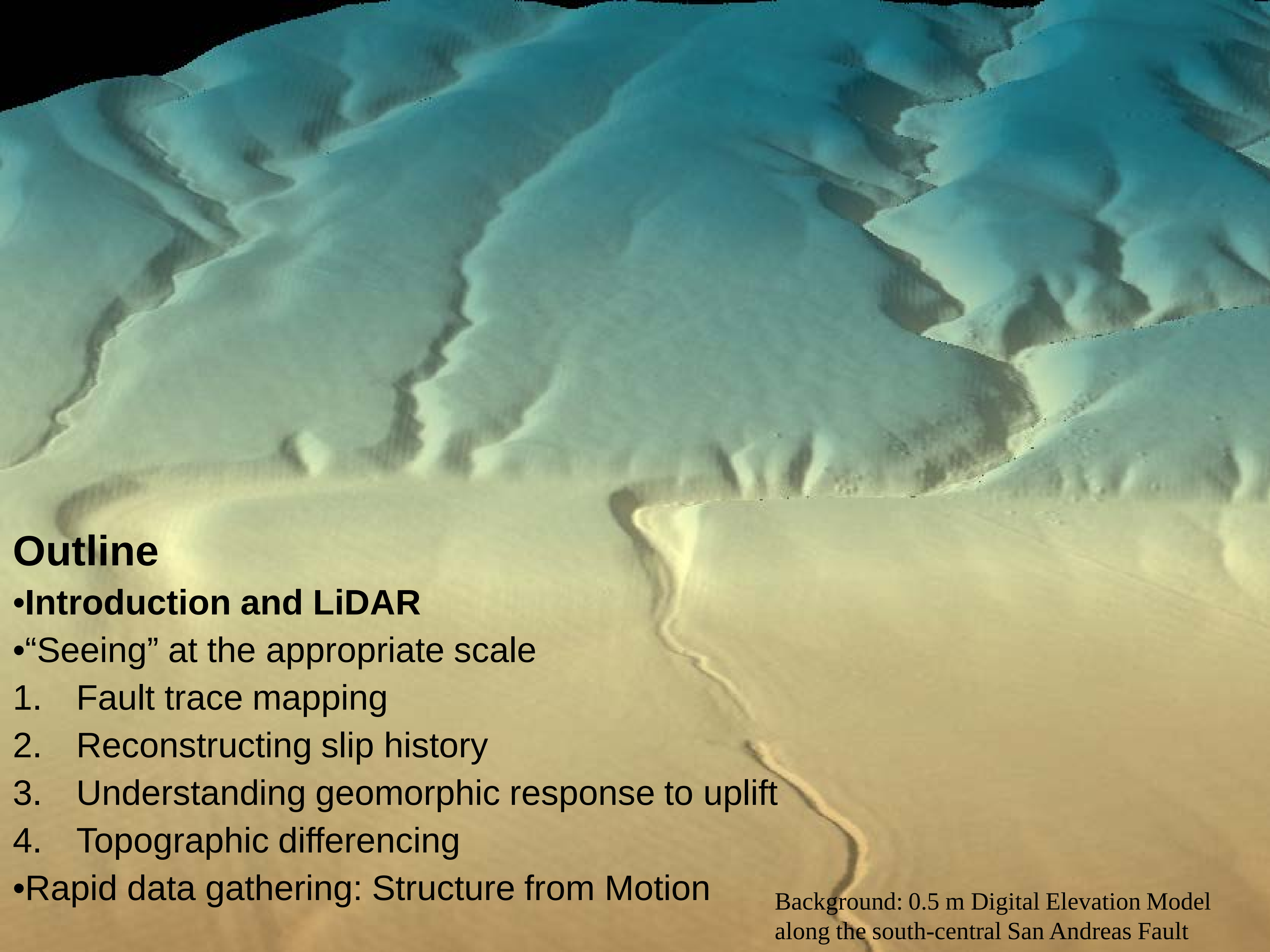
Before You Leave This
Be Able To

✓ Describe or sketch how def
and metamorphism occur in
continental rifts, rifted cont
margins, and mid-ocean rid

✓ Describe strike-slip faults, s
settings where they occur, a
features formed on the land

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;



Outline

- **Introduction and LiDAR**
- “Seeing” at the appropriate scale

1. Fault trace mapping
2. Reconstructing slip history
3. Understanding geomorphic response to uplift
4. Topographic differencing

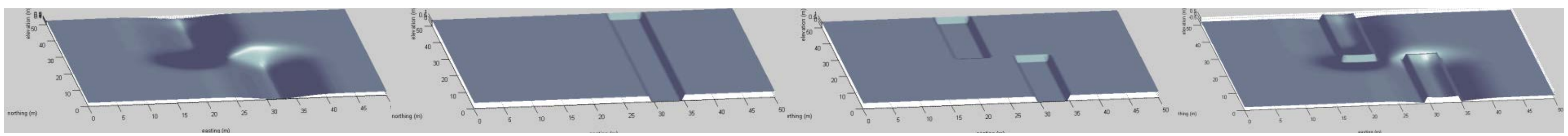
- Rapid data gathering: Structure from Motion

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

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.

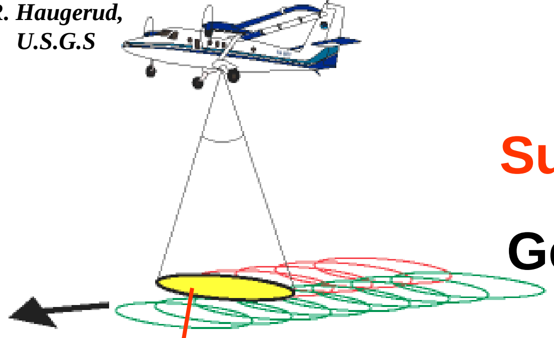
Current elevation = Original elevation + Tectonic displacement + Geomorphic displacement



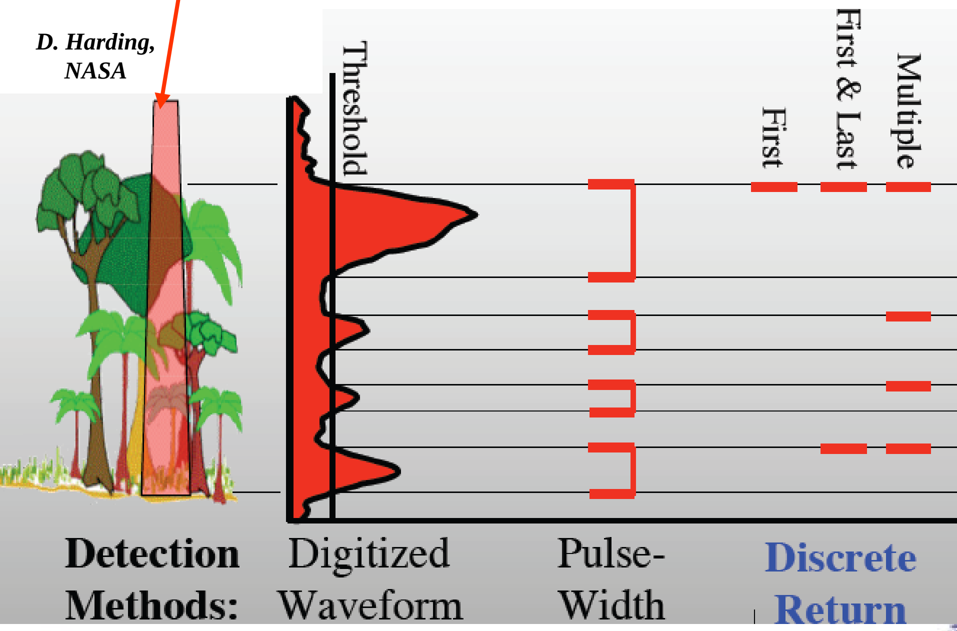
$$H(x,y,t) = H_0(x,y) + U(x,y,t,H) + V(x,y,t,H)$$

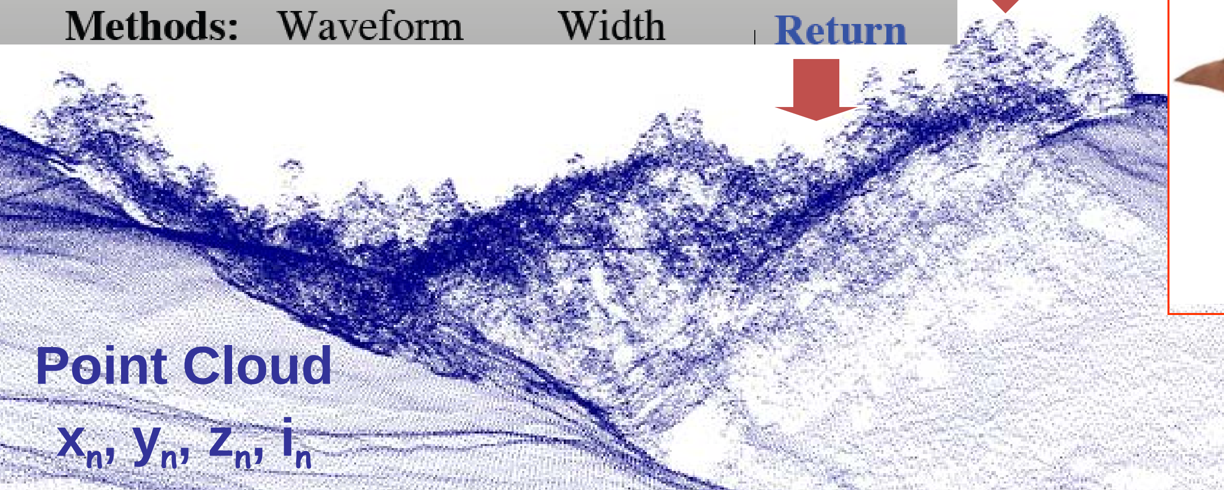
ALSM workflow:

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

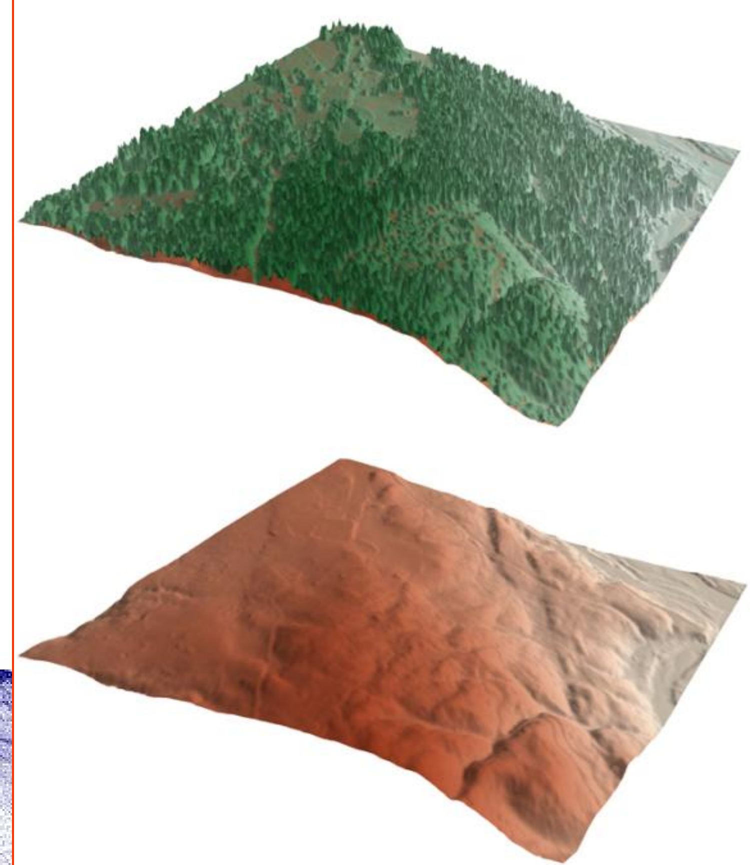


Geodesy and signal processing

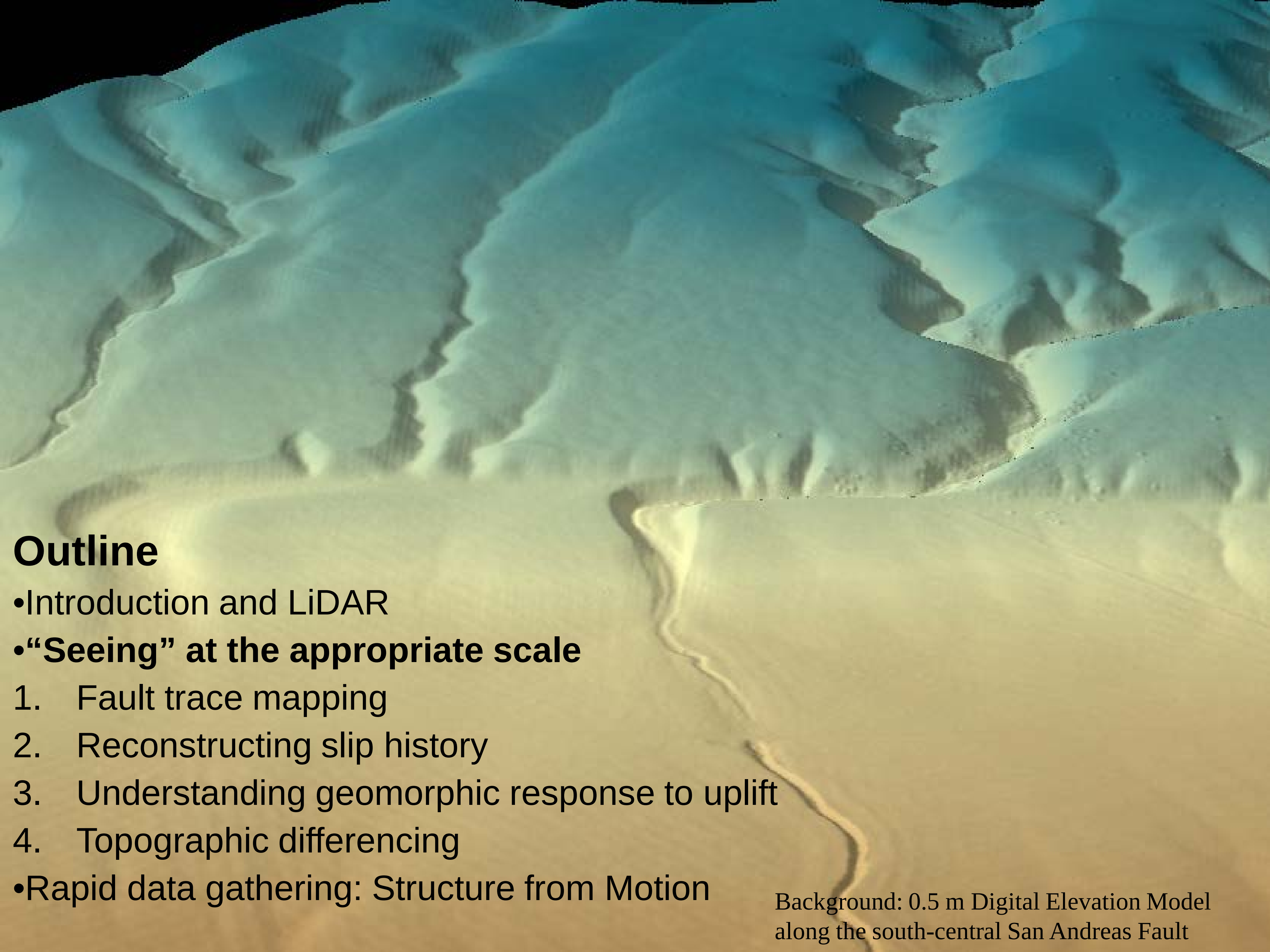




Gridded products



Answer science question



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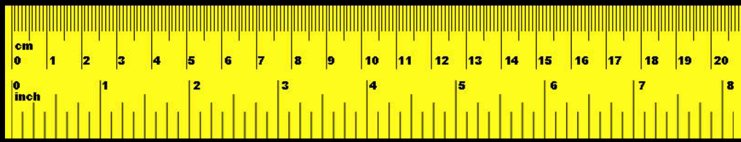
“Seeing” at the appropriate scale means measuring at the right scale



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

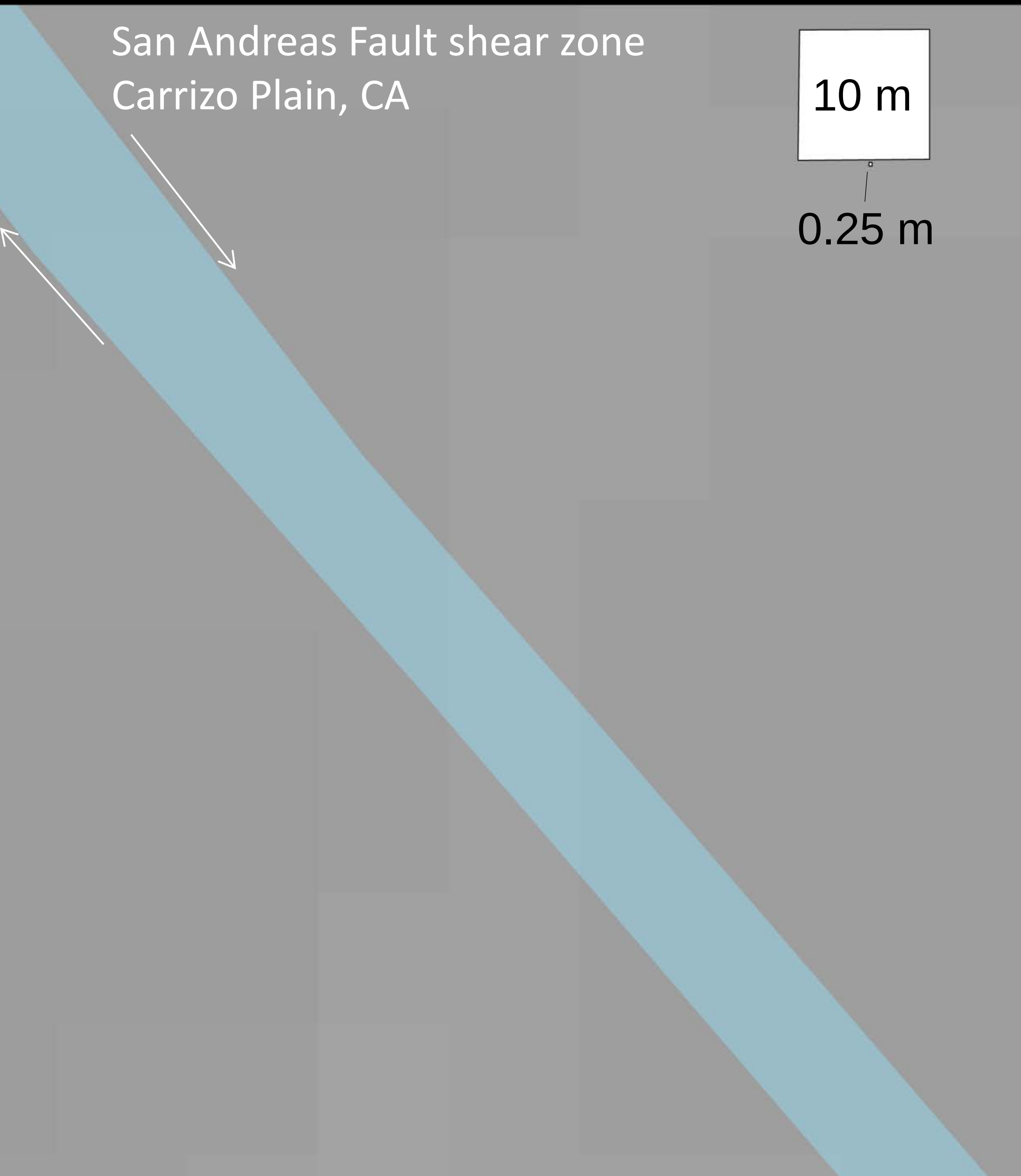
How long is the coast of Britain?
Statistical self-similarity and fractional dimension
Science: 156, 1967, 636-638

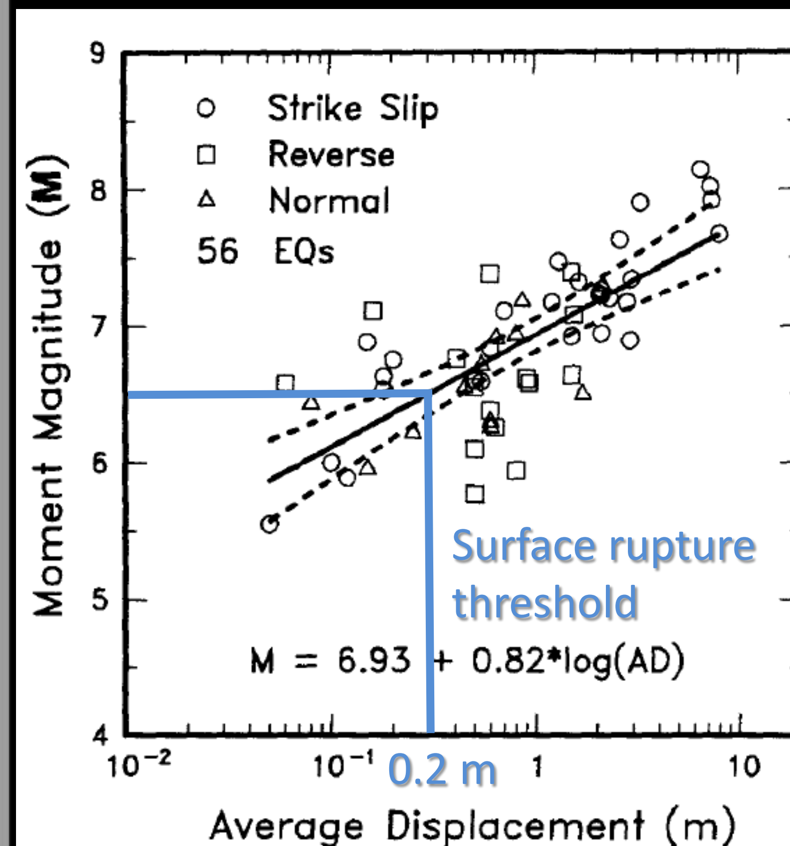
B. B. Mandelbrot

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

Measure fault slip at the appropriate scale

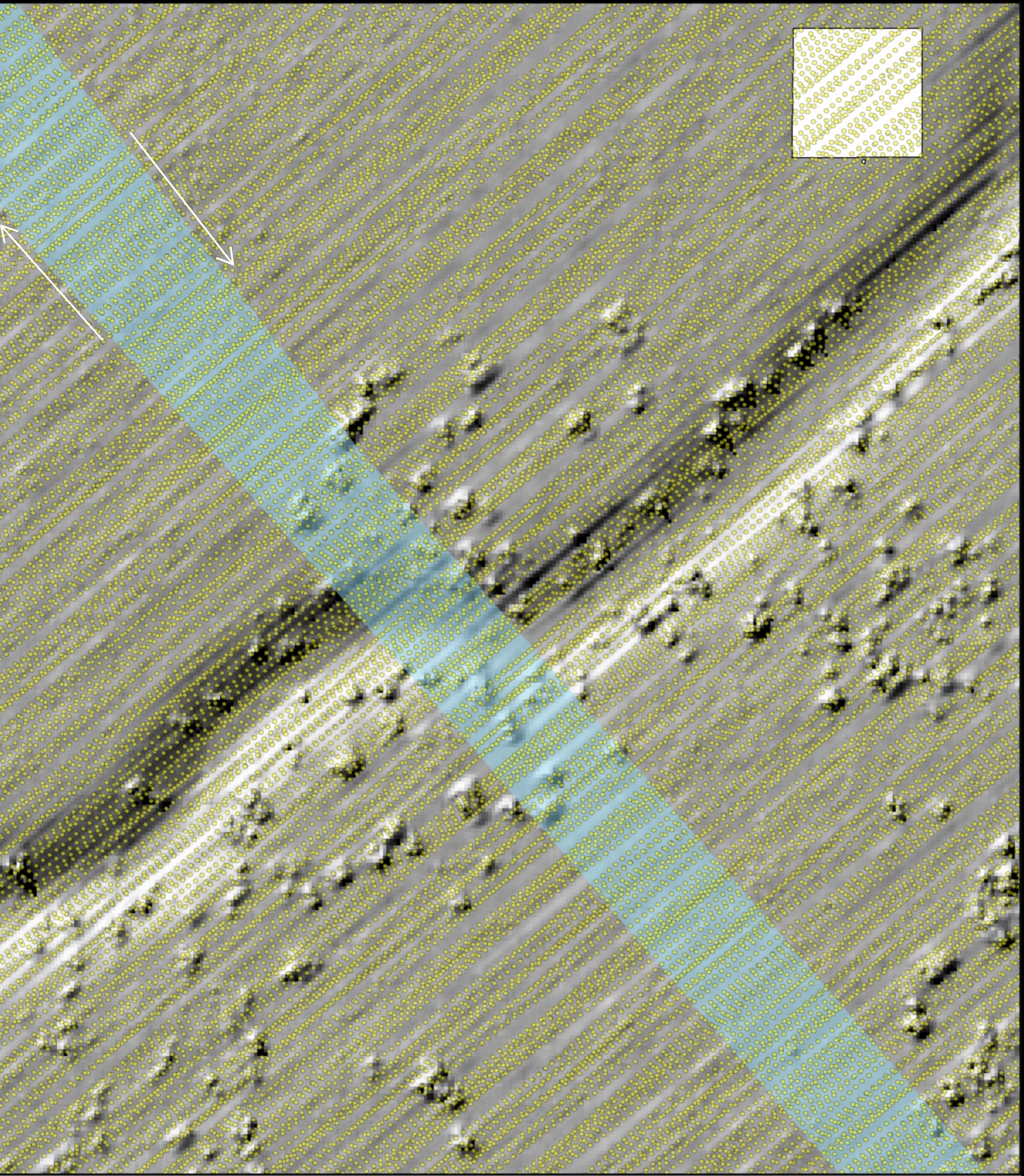
USGS NED 10 m per pixel DEM

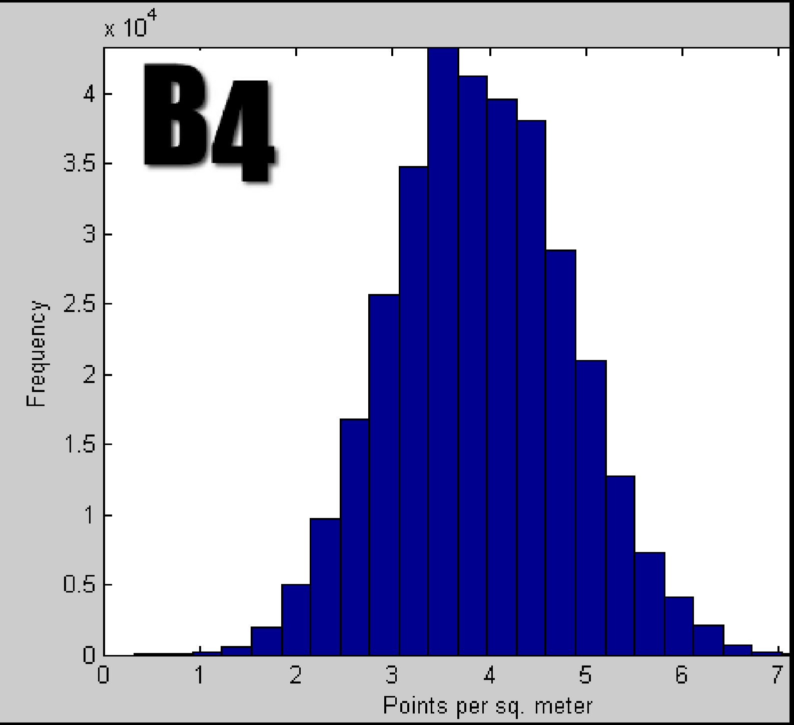




Measure fault slip at the appropriate scale

B4 LiDAR topography 0.25 m DEM

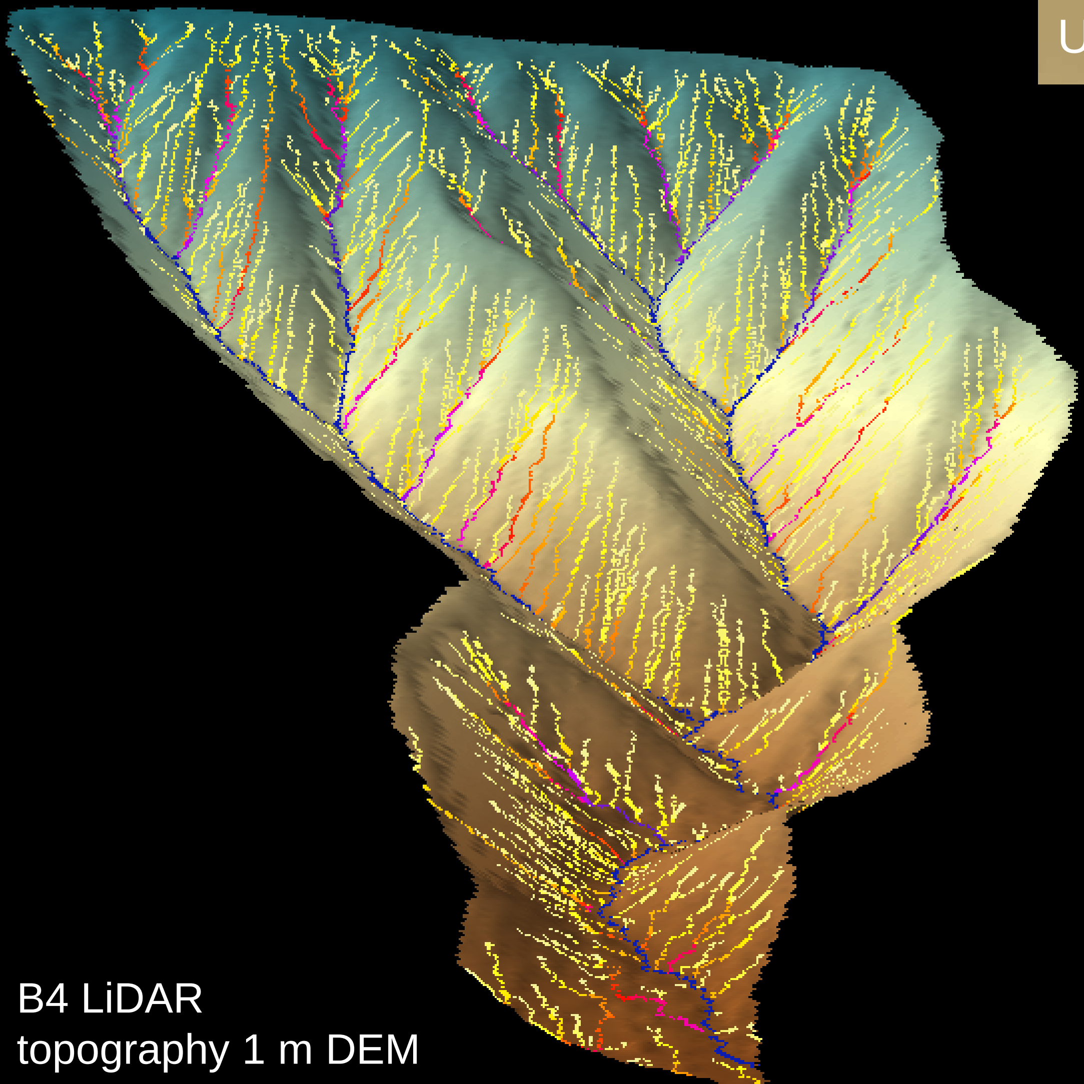




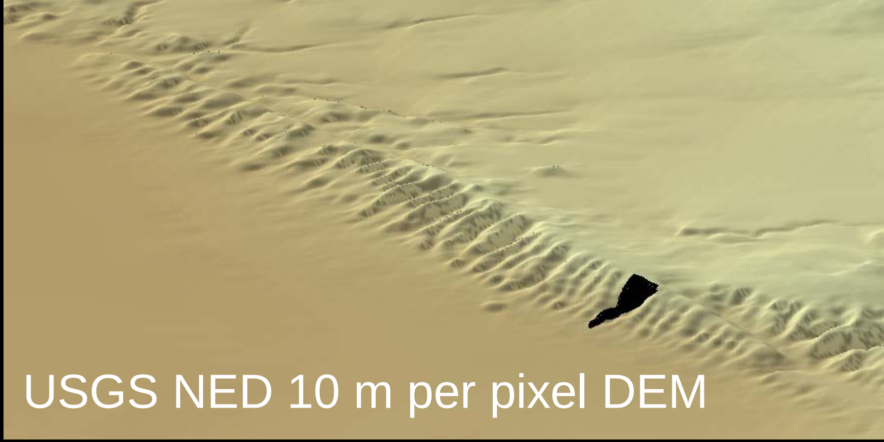
Mean ~4 shots/sq. m

Measure landscape characteristics at the appropriate scale

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



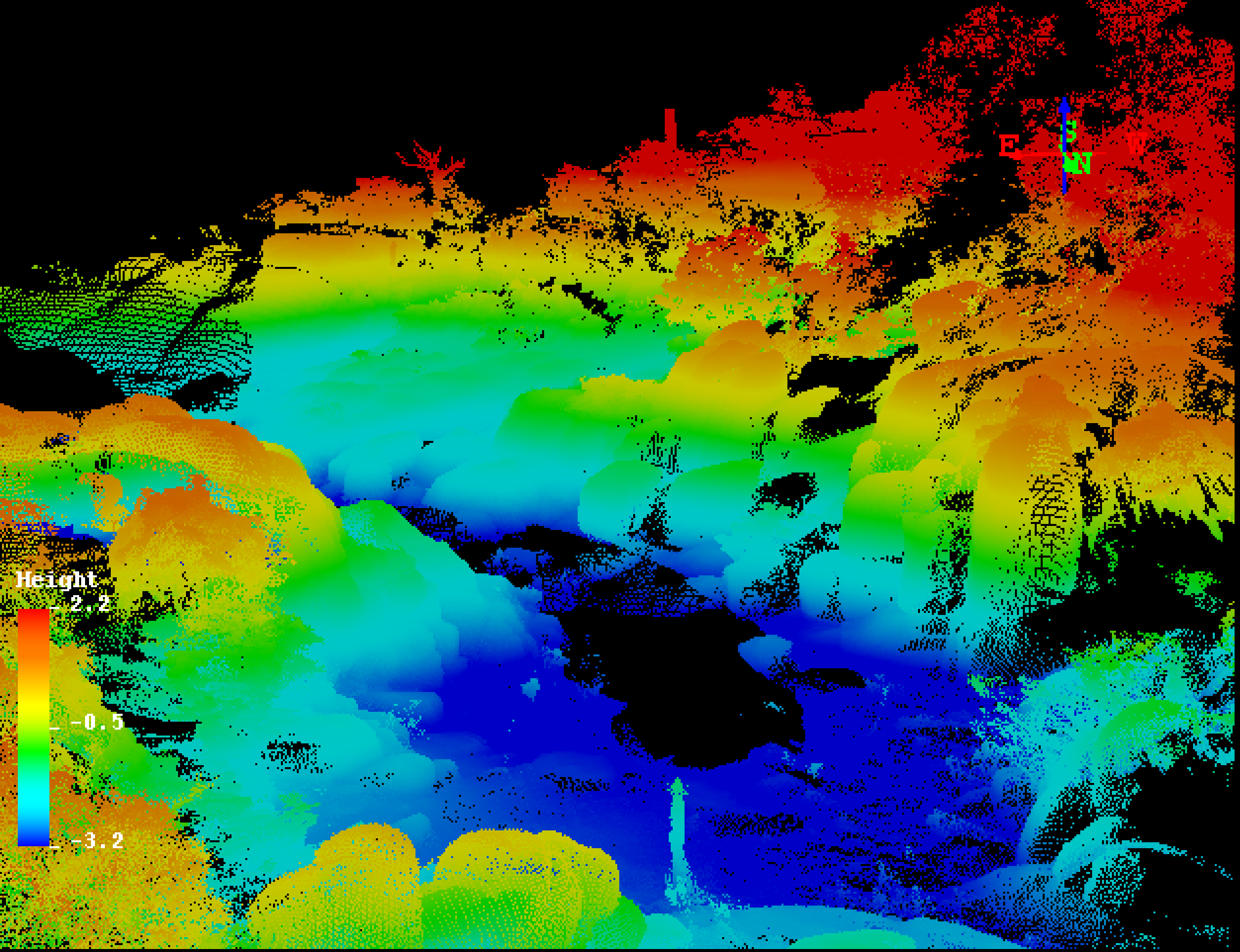
B4 LiDAR
topography 1 m DEM



USGS NED 10 m per pixel DEM

Meter scale features


Laser Scanner field operations
TCP/IP 192

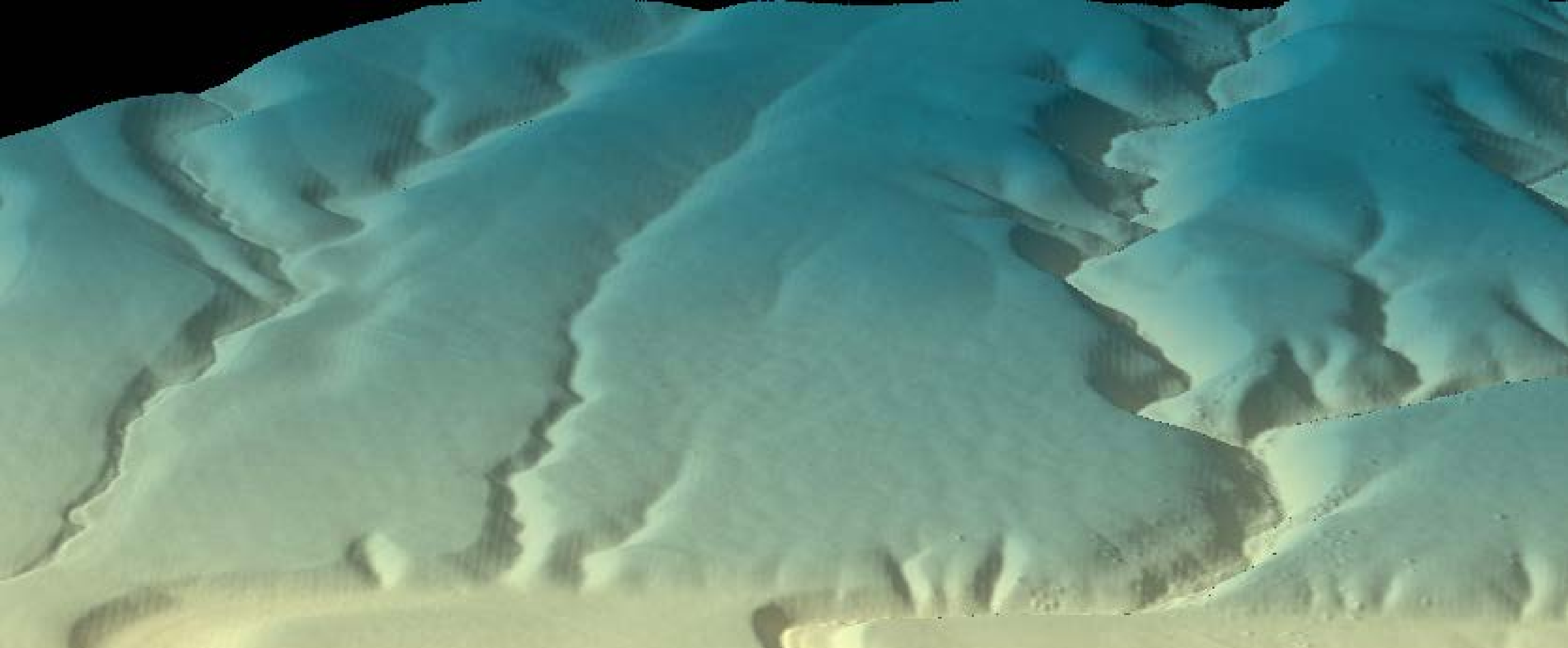


Terrestrial Laser Scanning Applications in Paleoseismology

•Earthquakes disrupt the earth's surface at cm to m scales
•Depositional and erosional response is typically on a similar scale
•We need absolute measurement capability sufficient to characterize these changes in challenging geometric arrangements

Haddad, et al., 2012

http://www.utdallas.edu/research/interface/resource_intro.html



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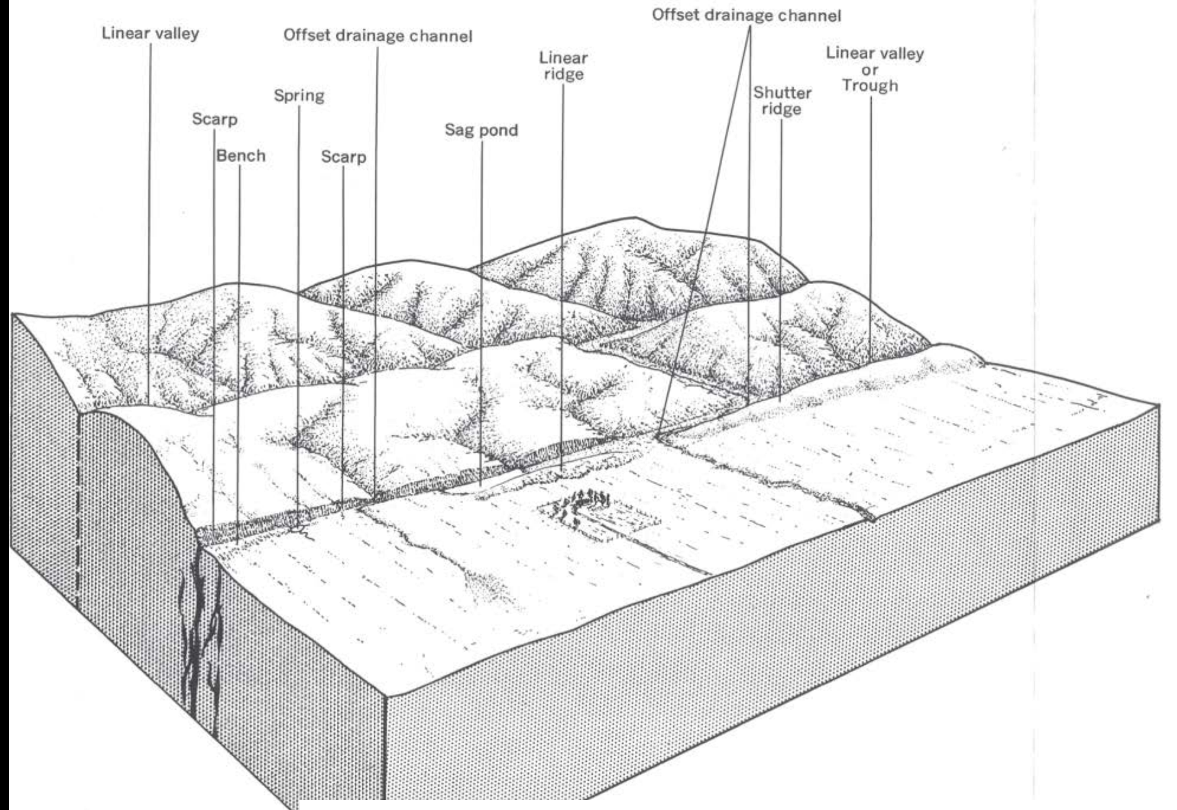
Background: 0.5 m Digital Elevation Model
along the south-central San Andreas Fault

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

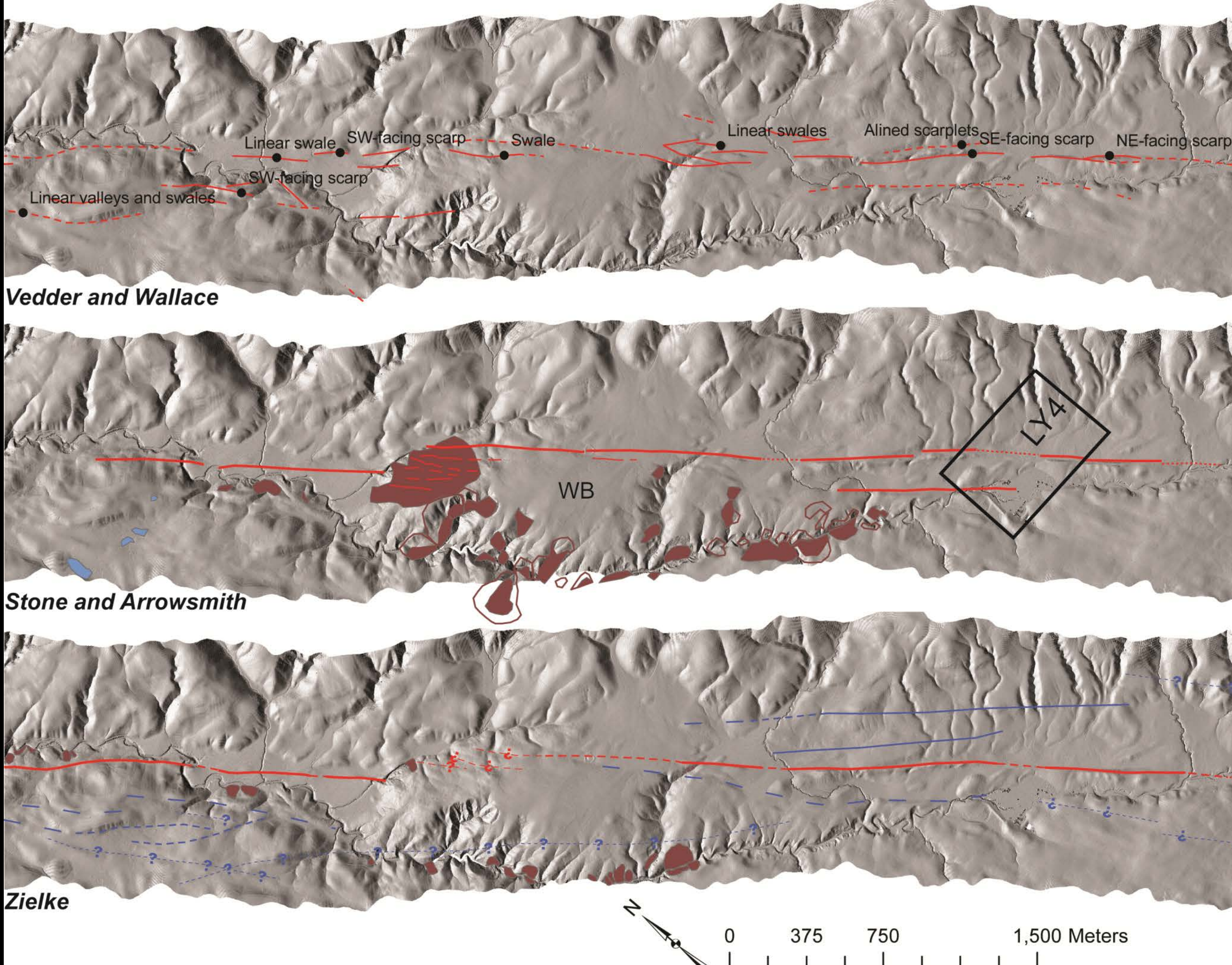
Stone and Arrowsmith

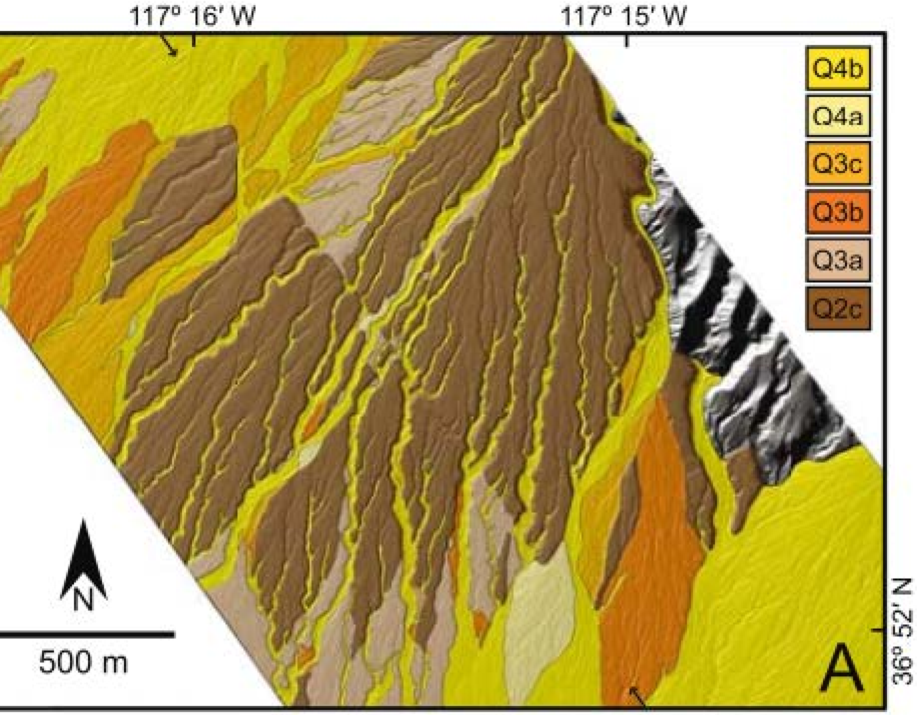
- Fault trace
- Fault trace, concealed
- Fault trace, inferred
- Lineament
- Landslide deposit
- Landslide scarp
- Sag

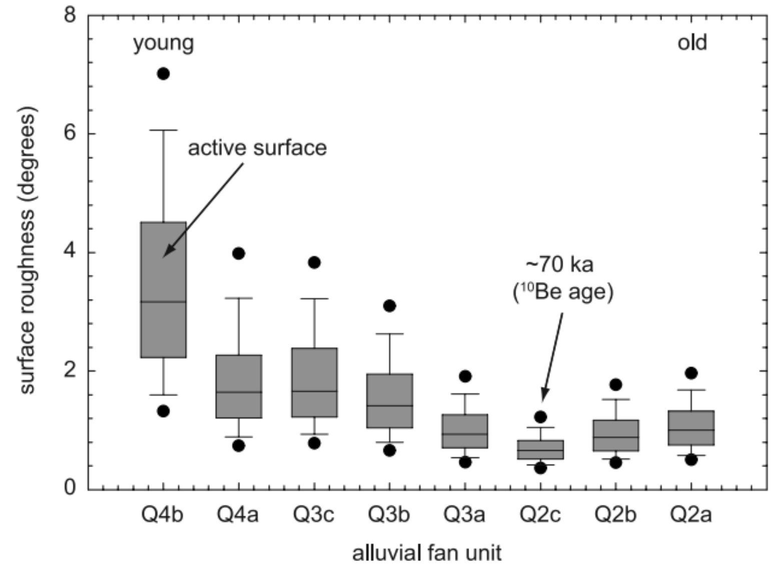
Zielke, this study

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

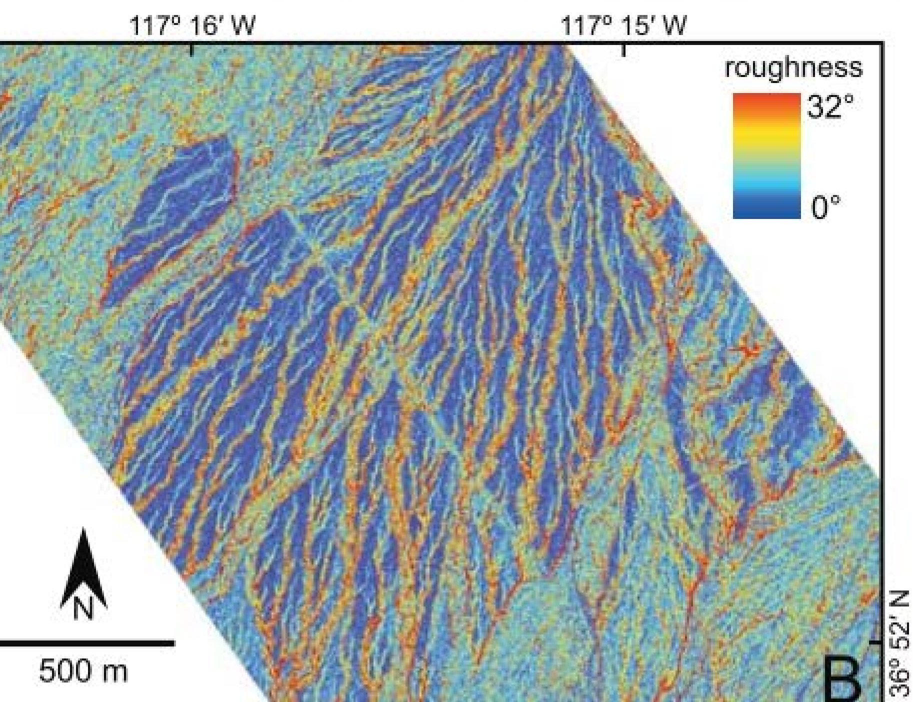
- Fault trace, certain
- Fault trace, inferred
- ? Fault trace, queried
- Fault trace, uncertain
- Landslide deposit and scarp

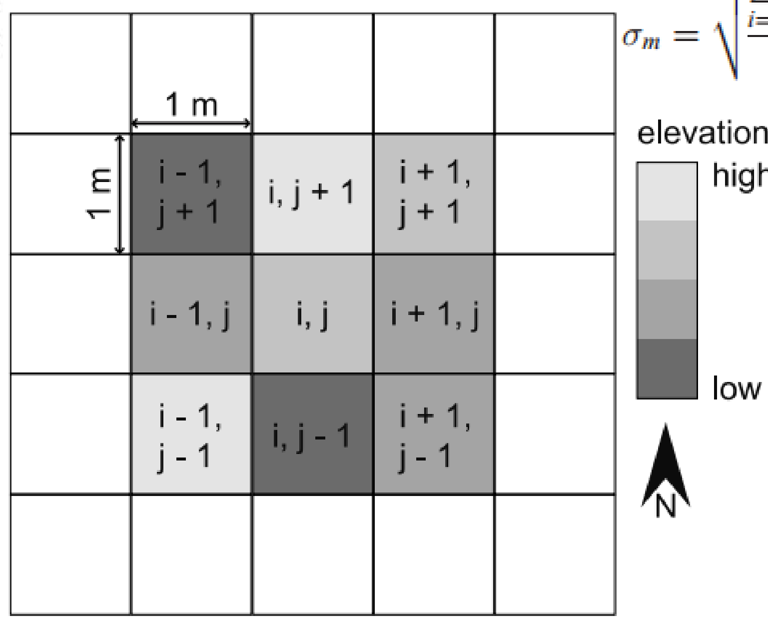

Linear swale
SW-facing scarp
Swale
Linear swales
Alined scarplets
SE-facing scarp
NE-facing scarp
SW-facing scarp
Linear valleys and swales
Vedder and Wallace
LY4
WB
Stone and Arrowsmith
Zielke
N
0
375
750
1,500 Meters





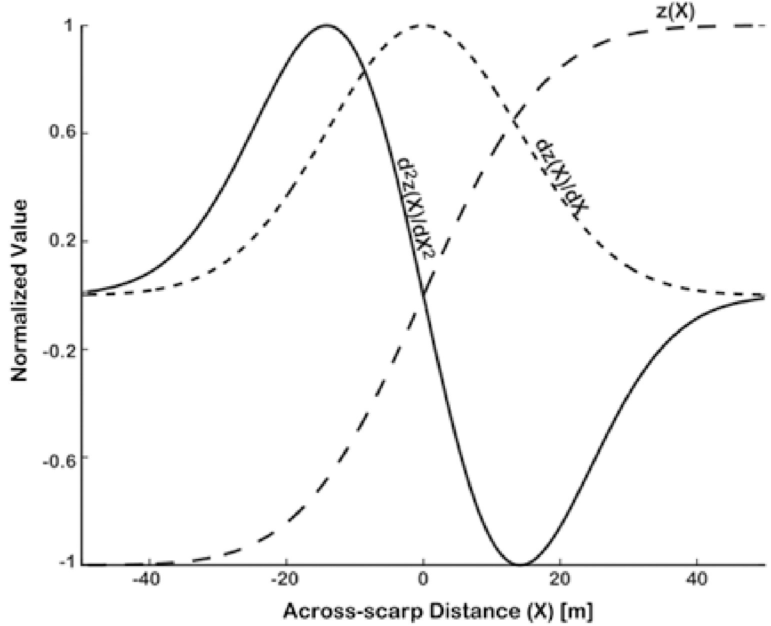
$$\sigma_m = \sqrt{\frac{\sum_{i=1}^{n}(m_i - \overline{m})^2}{n}},$$

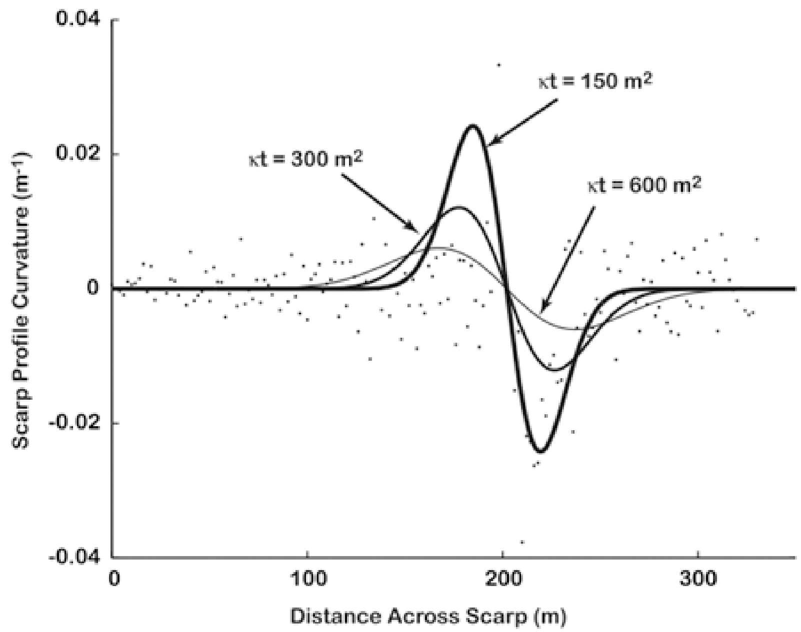




Characterizing arid region alluvial fan surface roughness with airborne laser swath mapping digital topographic data

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

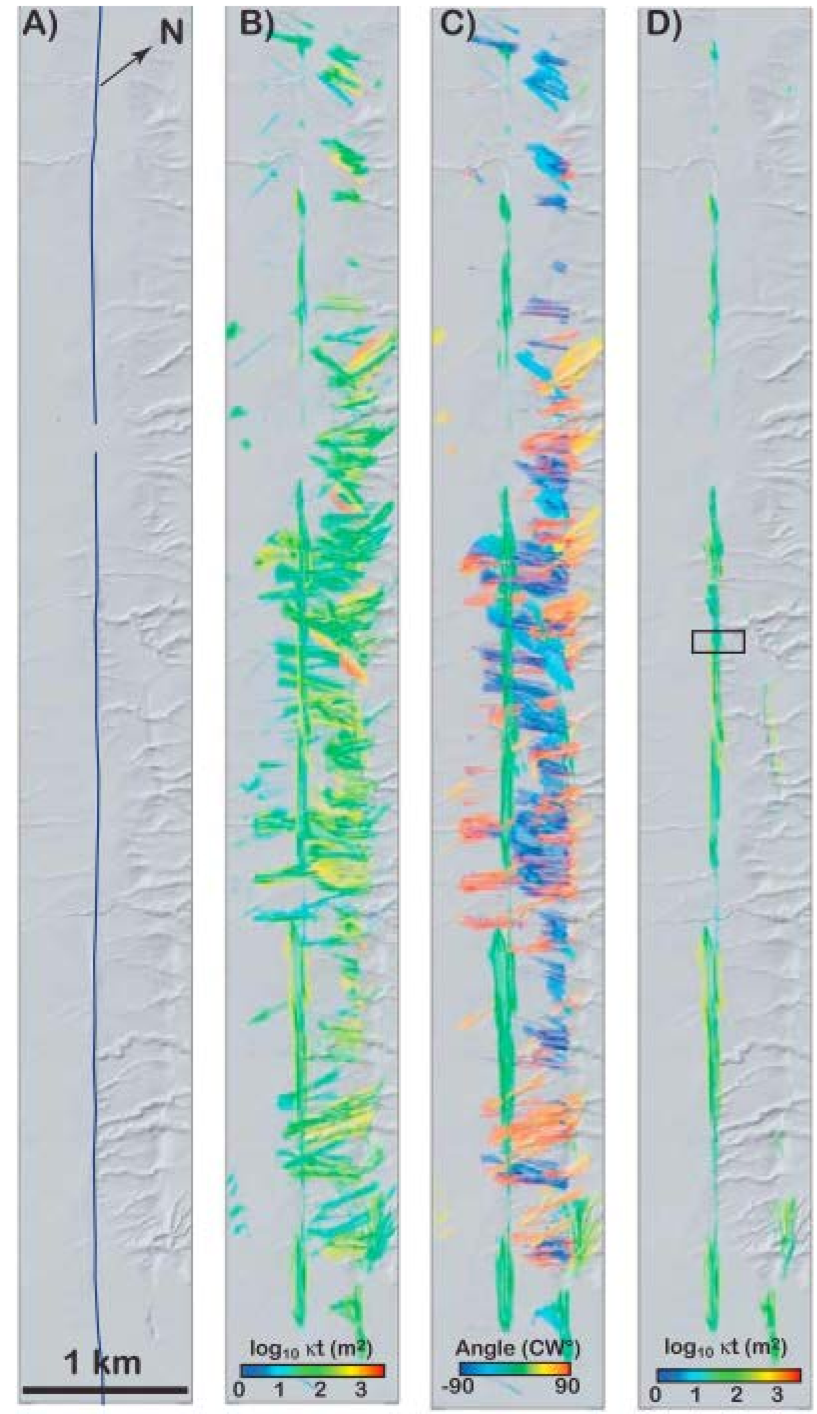


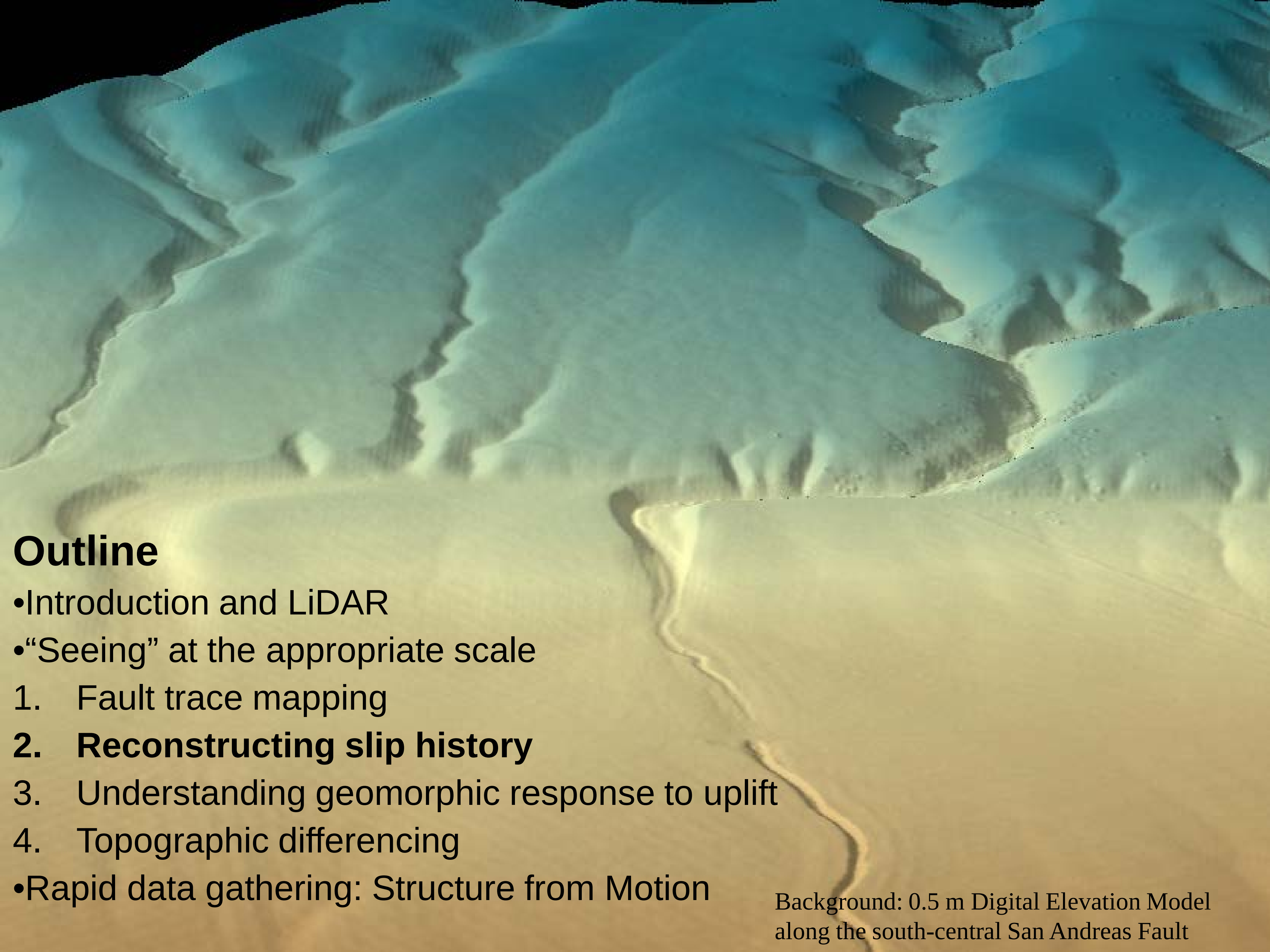


Morphologic dating of fault scarps using airborne laser swath mapping (ALSM) data

GRL, 2010

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





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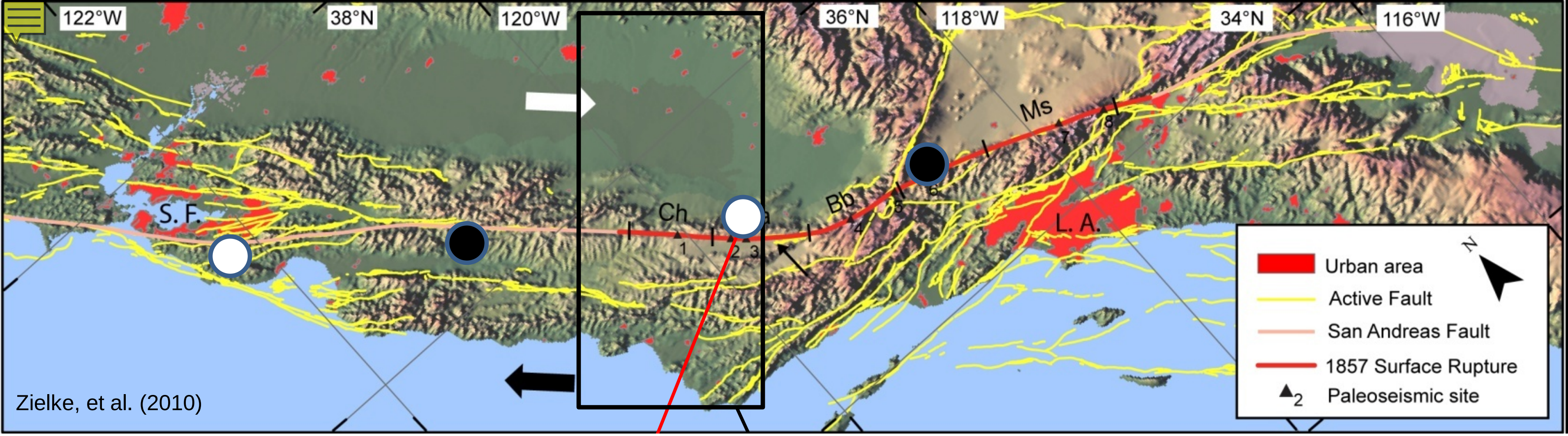
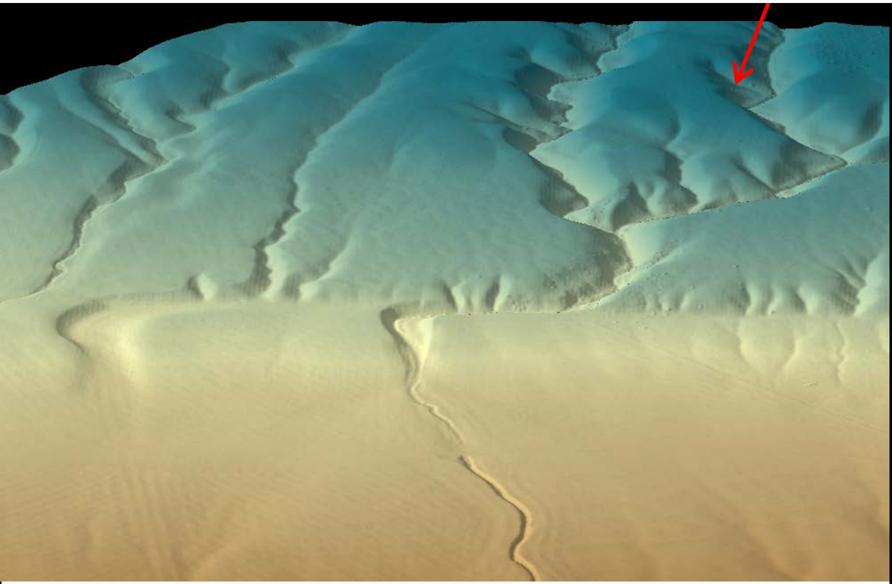
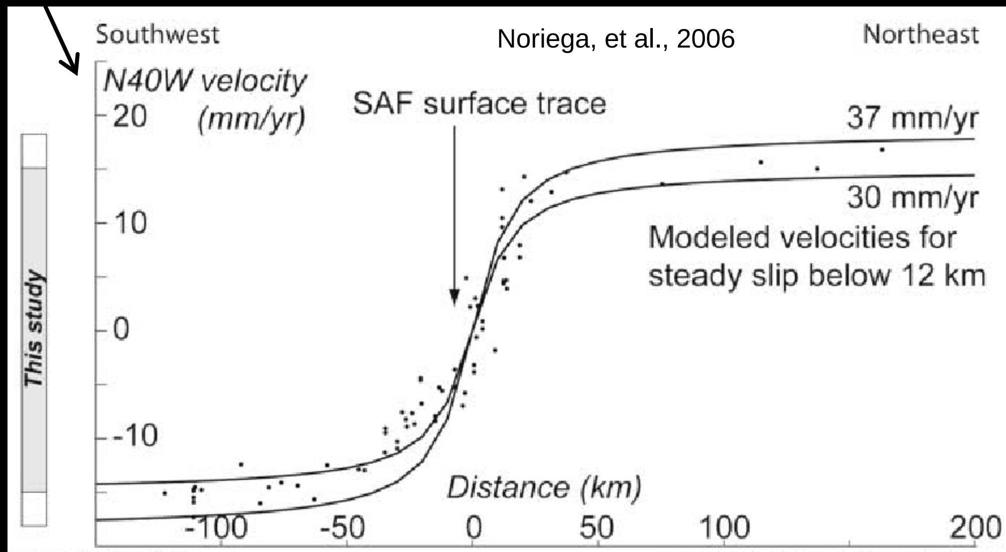


● Long term offset: 320 km since 24 Ma along major fault within plate boundary fault array



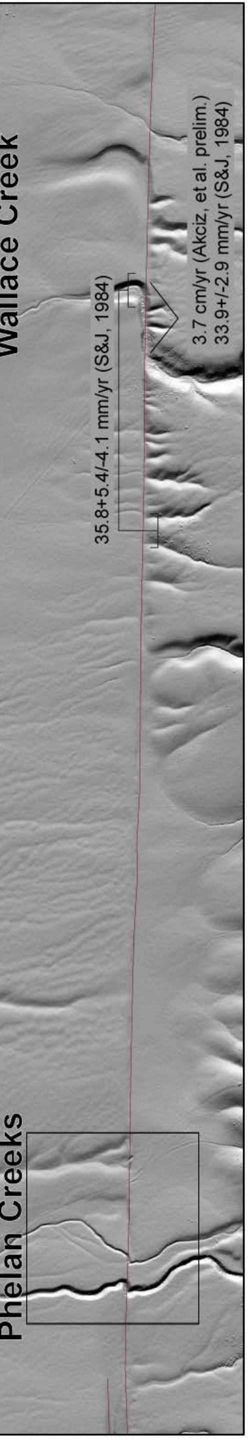
Slip rate of 34 mm/yr localized across <10m since at least 13.5 ka

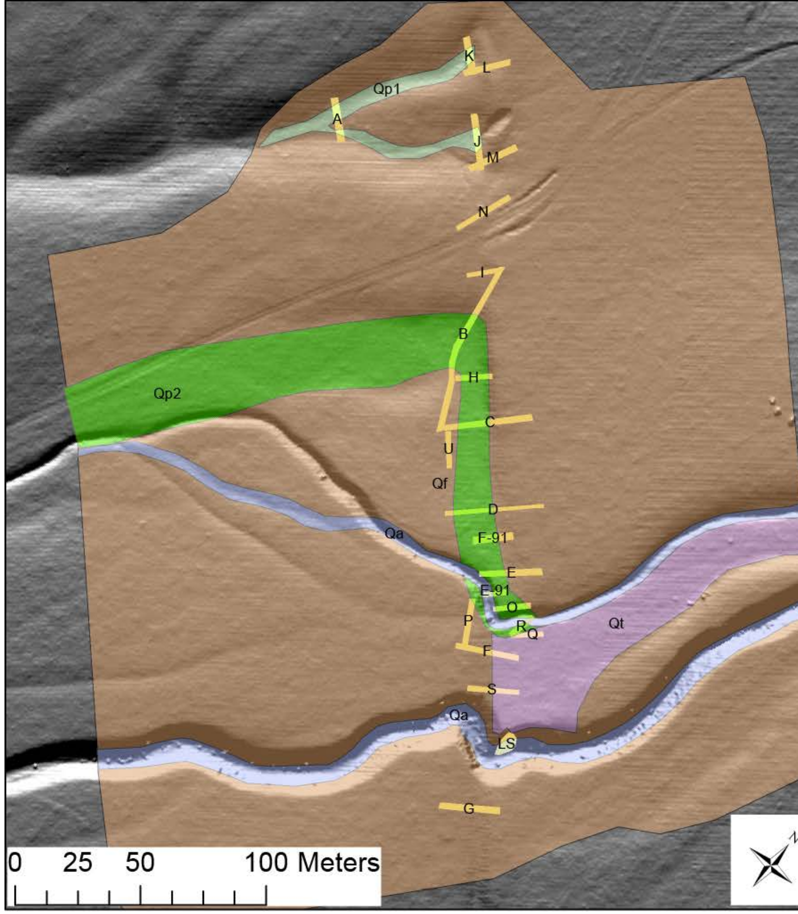
Sieh and Jahns (1984)

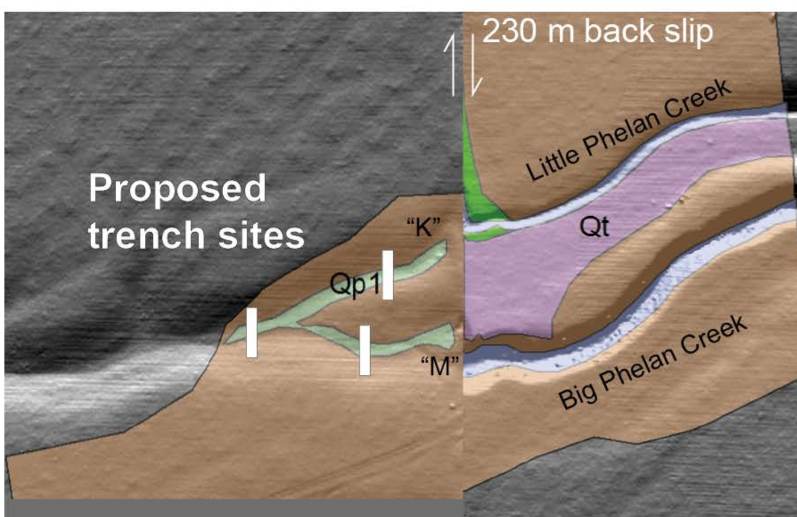


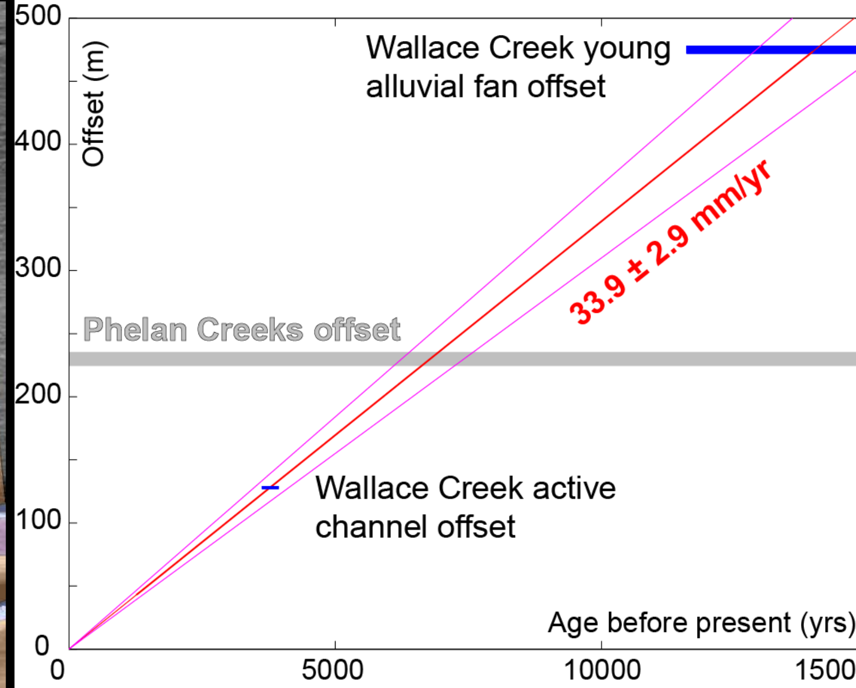
Steady strain accumulation by deep slip at 30-37 mm/yr over decadal time scale from geodesy

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

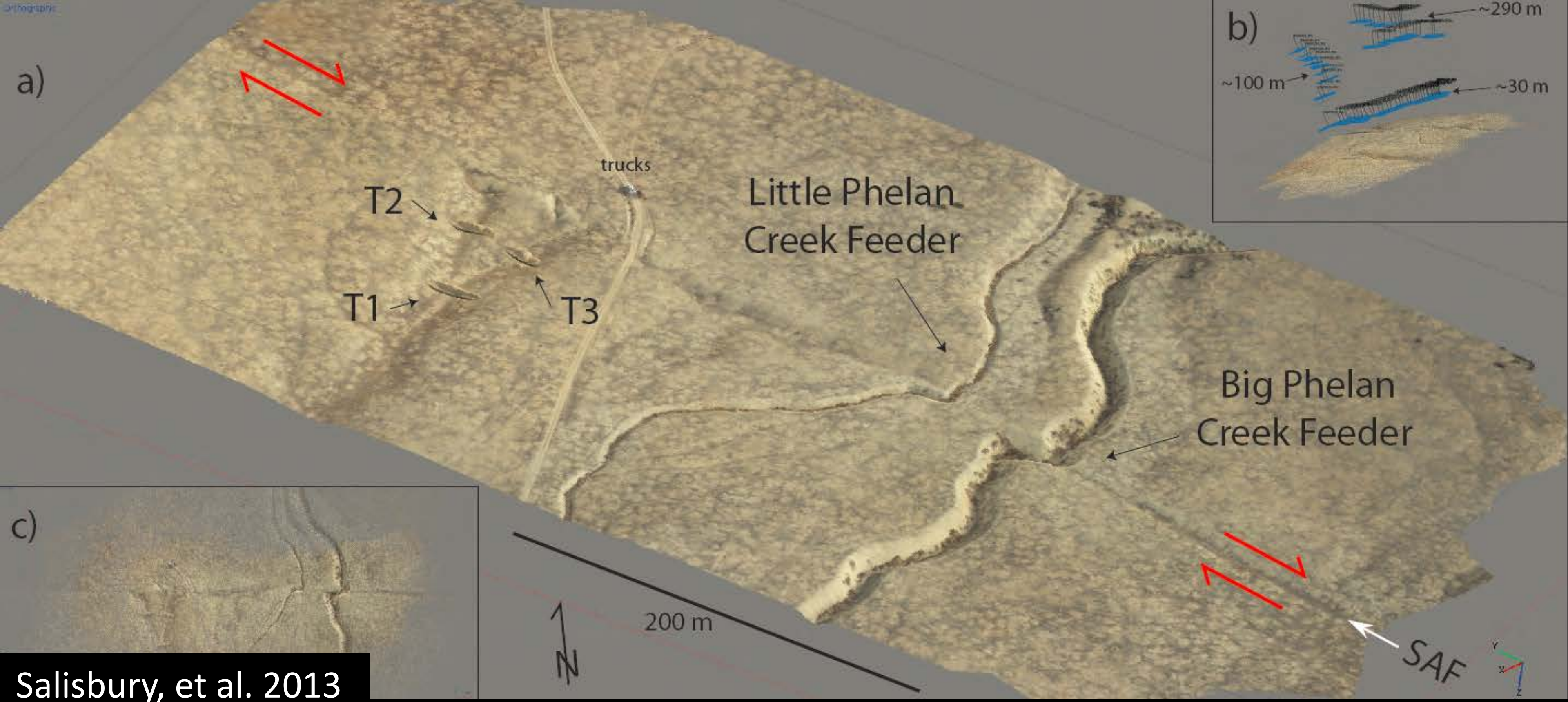






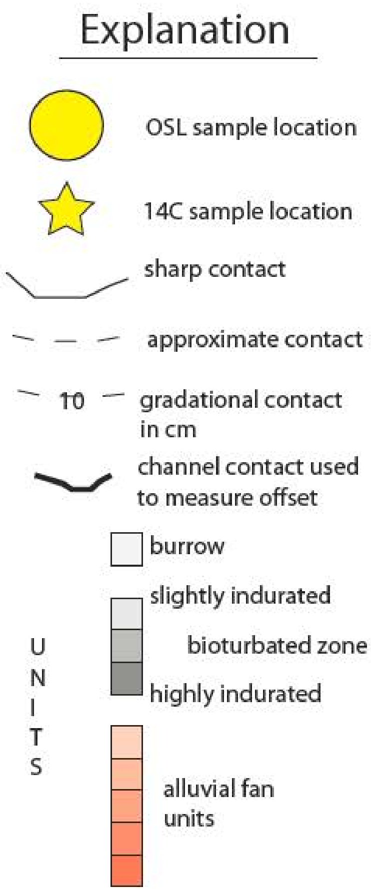


Opportunity to to update the central San Andreas fault slip rate at Phelan Creeks. How does it compare with the rate determinations from Wallace Creek?



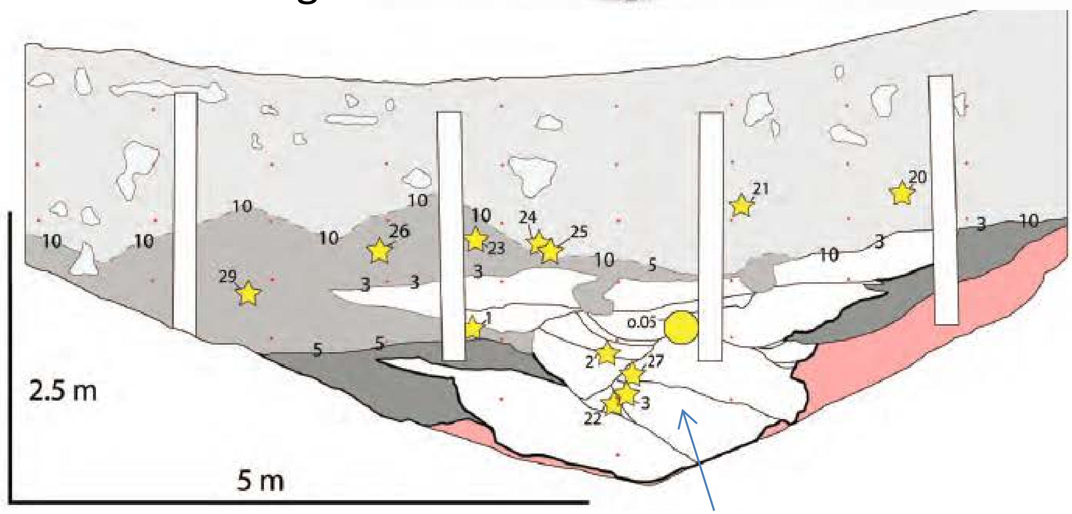
Phelan Creeks:
Structure from Motion topography and image texture

Phelan Creeks



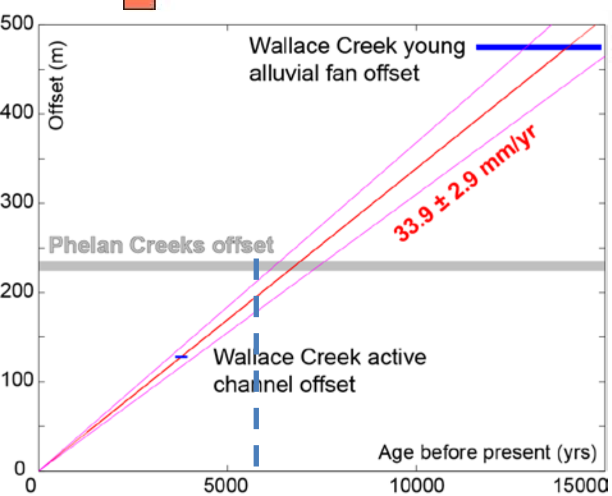
b) T3east

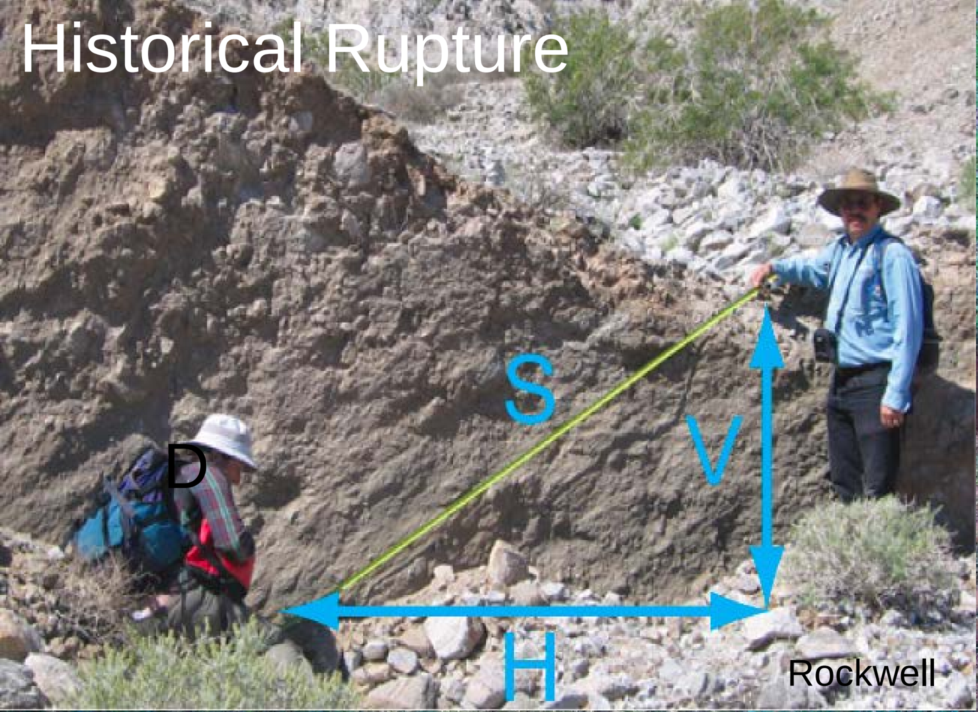
SfM trench image

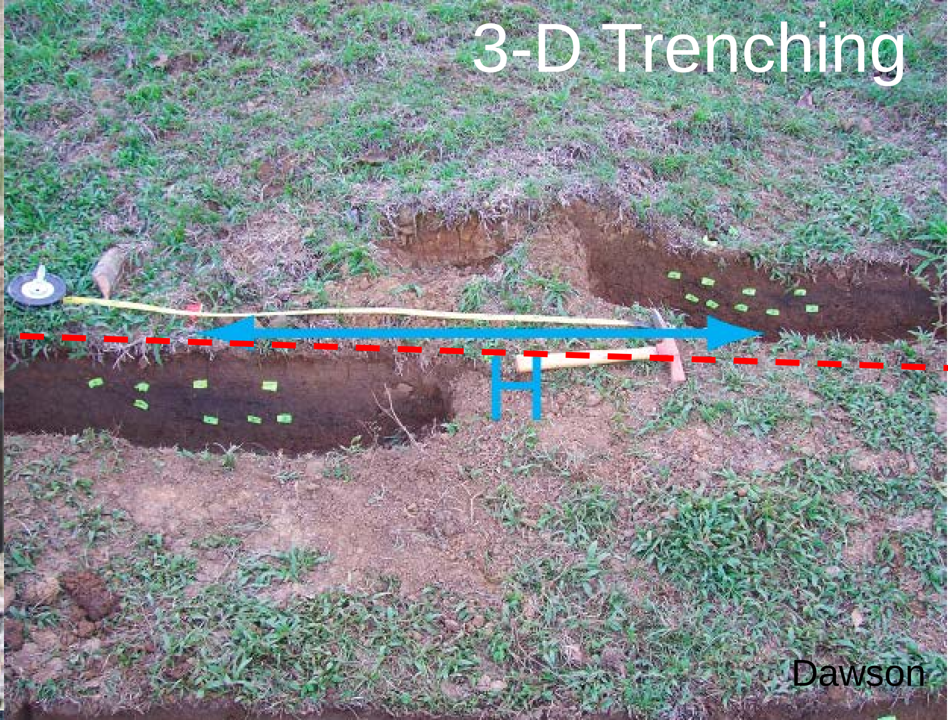


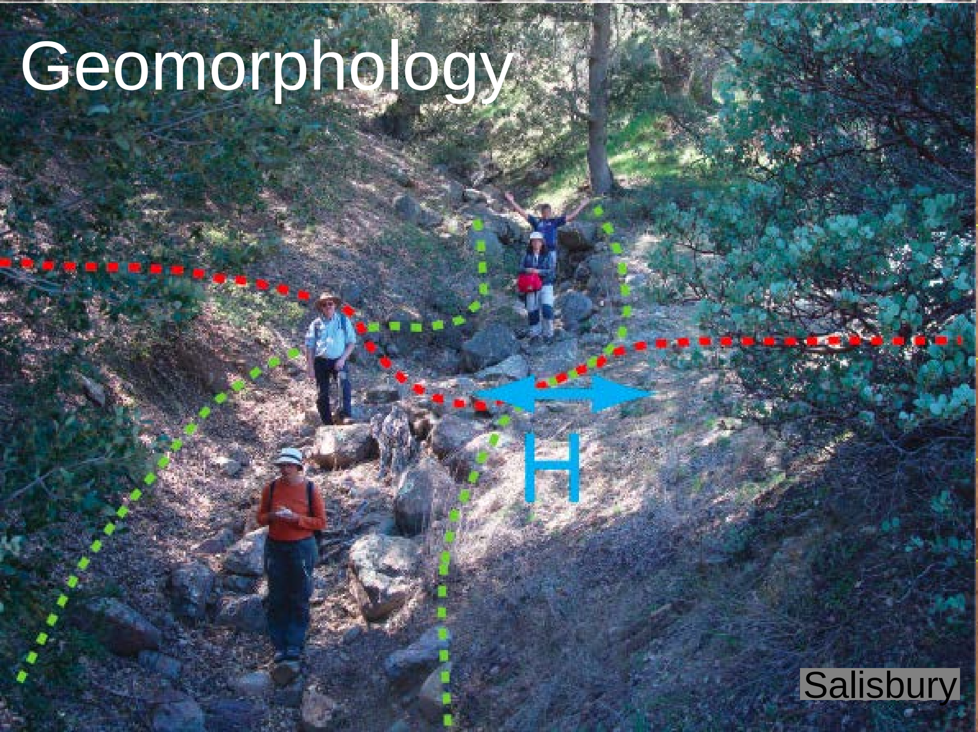
preliminary OSL age estimates of 5.6 +/- 0.3 and 6.0 +/- 0.4 ka

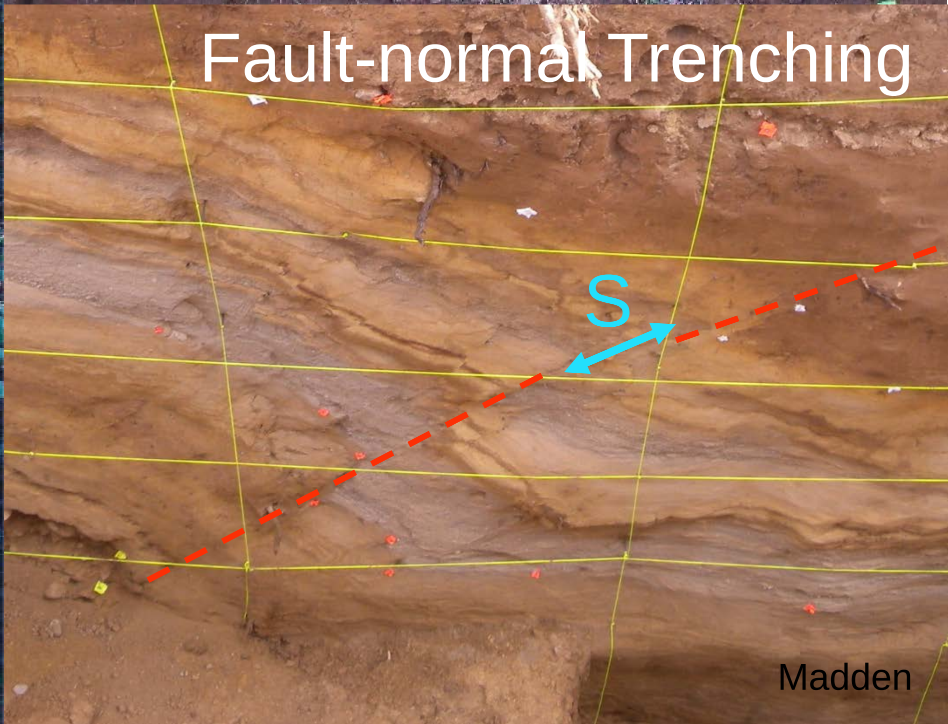
Salisbury, et al. 2013



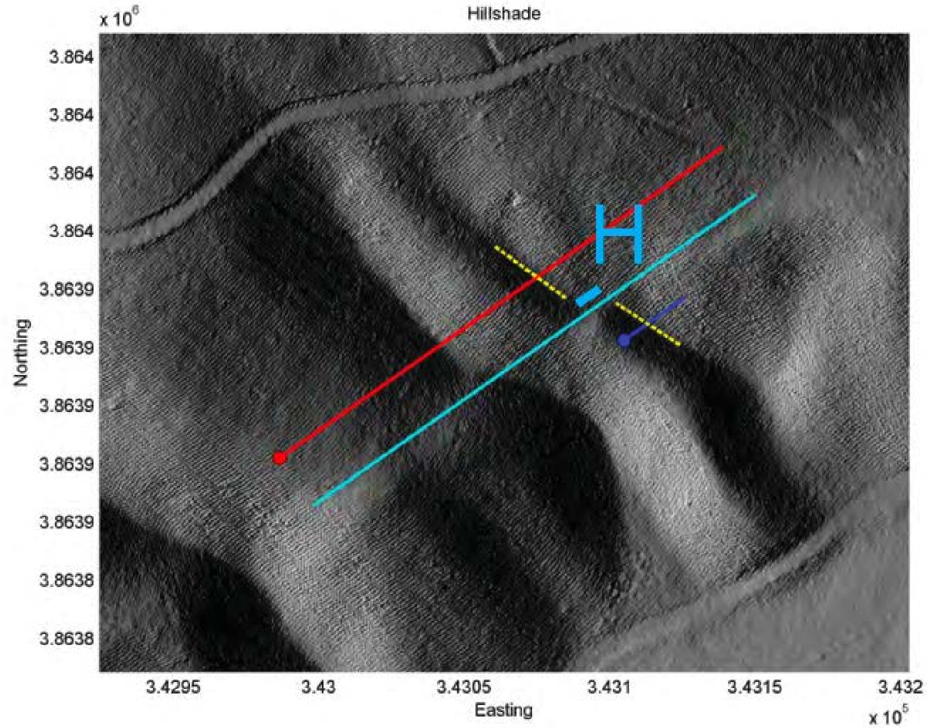

Historical Rupture
S
V
D
H
Rockwell

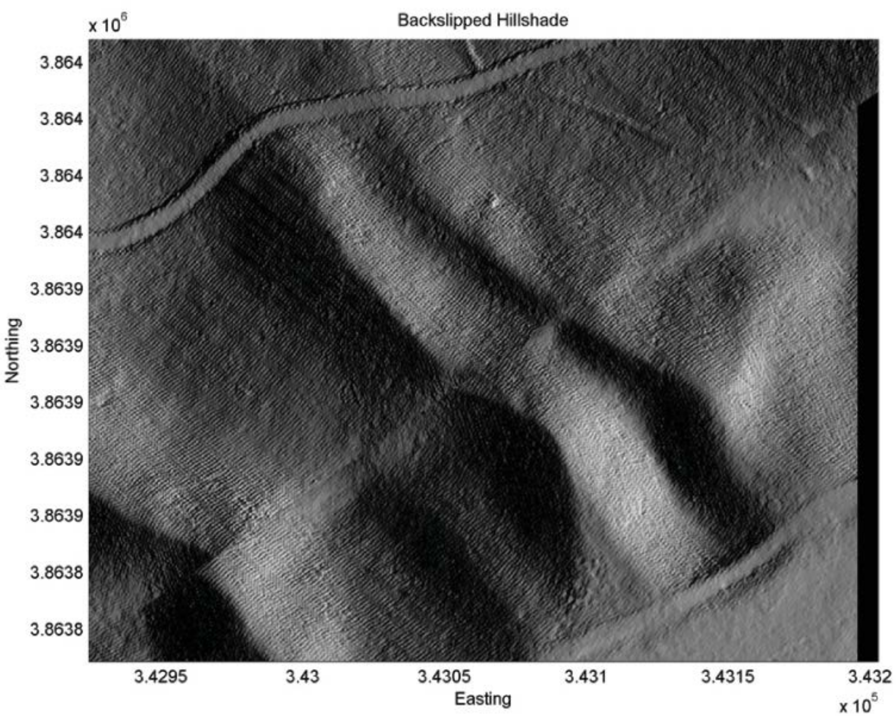

3-D Trenching
H
Dawson

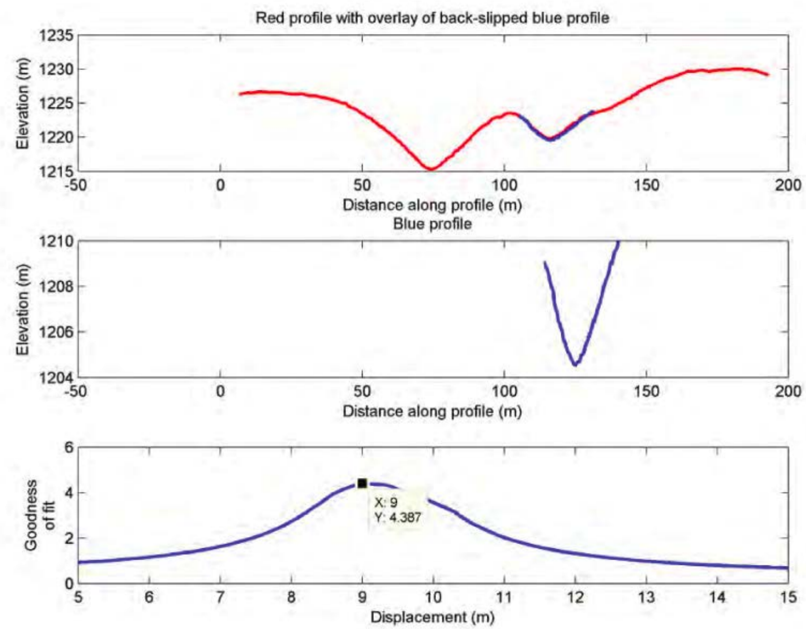

Geomorphology
H
Salisbury

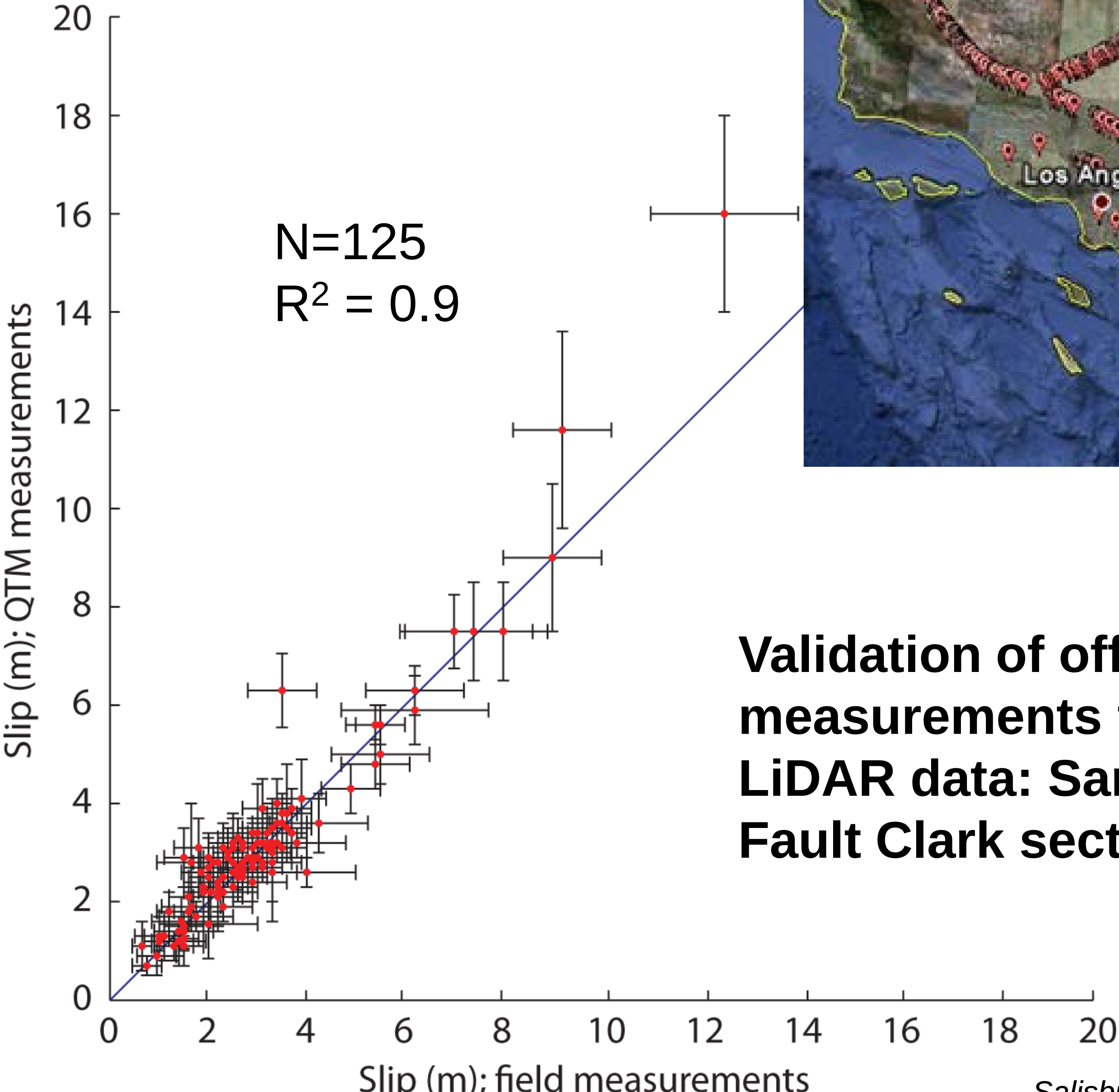

Fault-normal Trenching
S
Madden

LiDAR Measurements



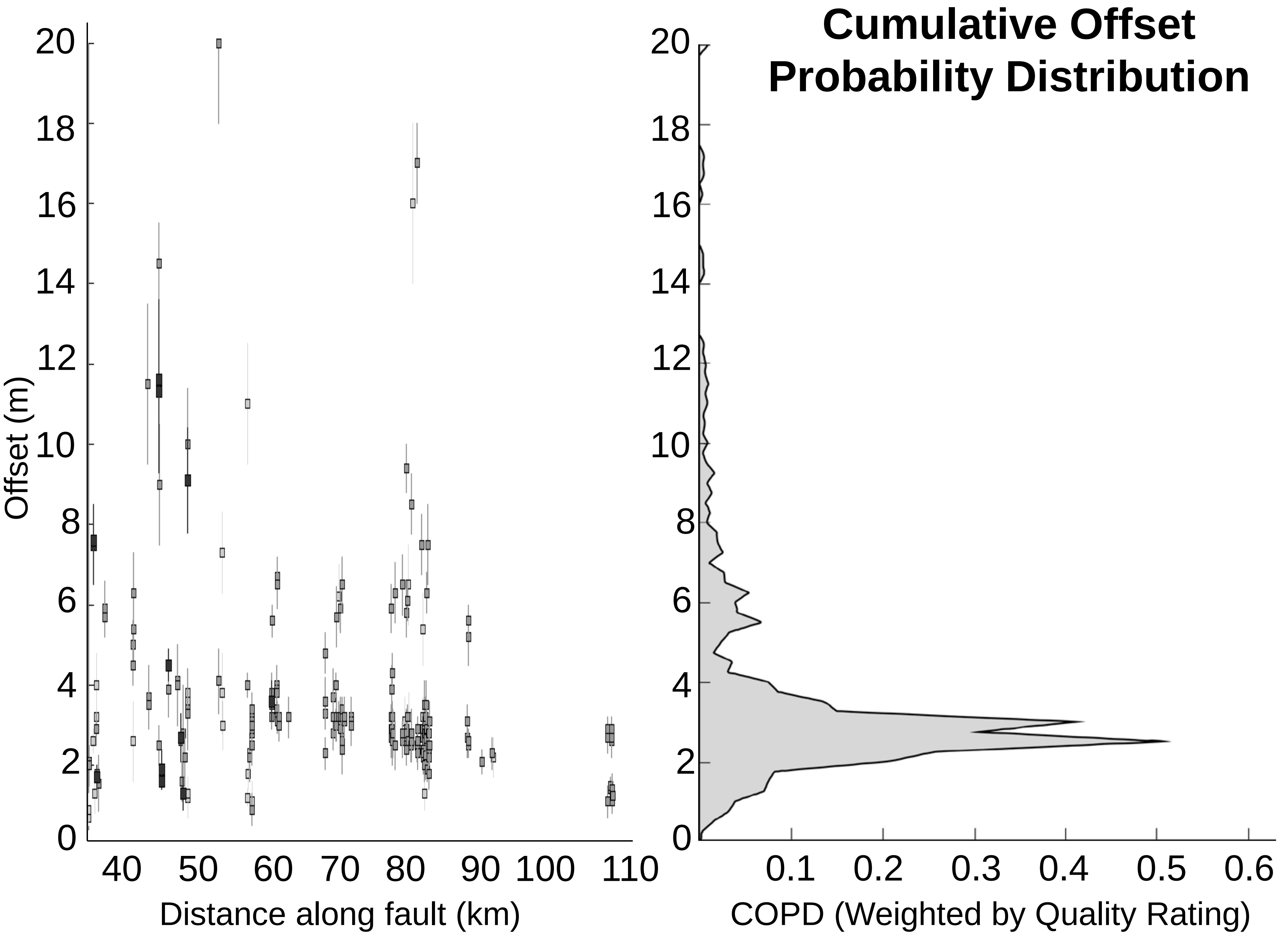


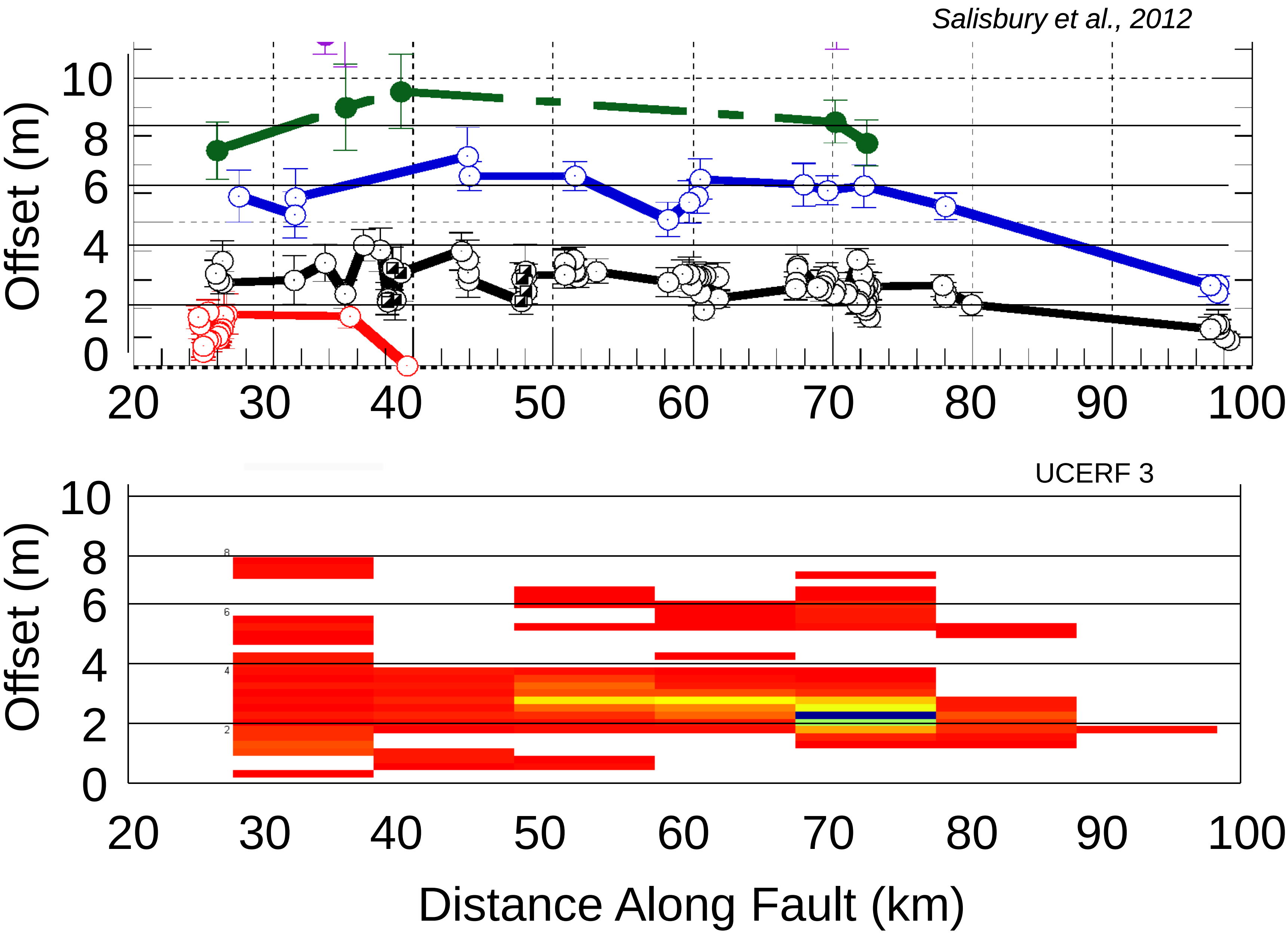


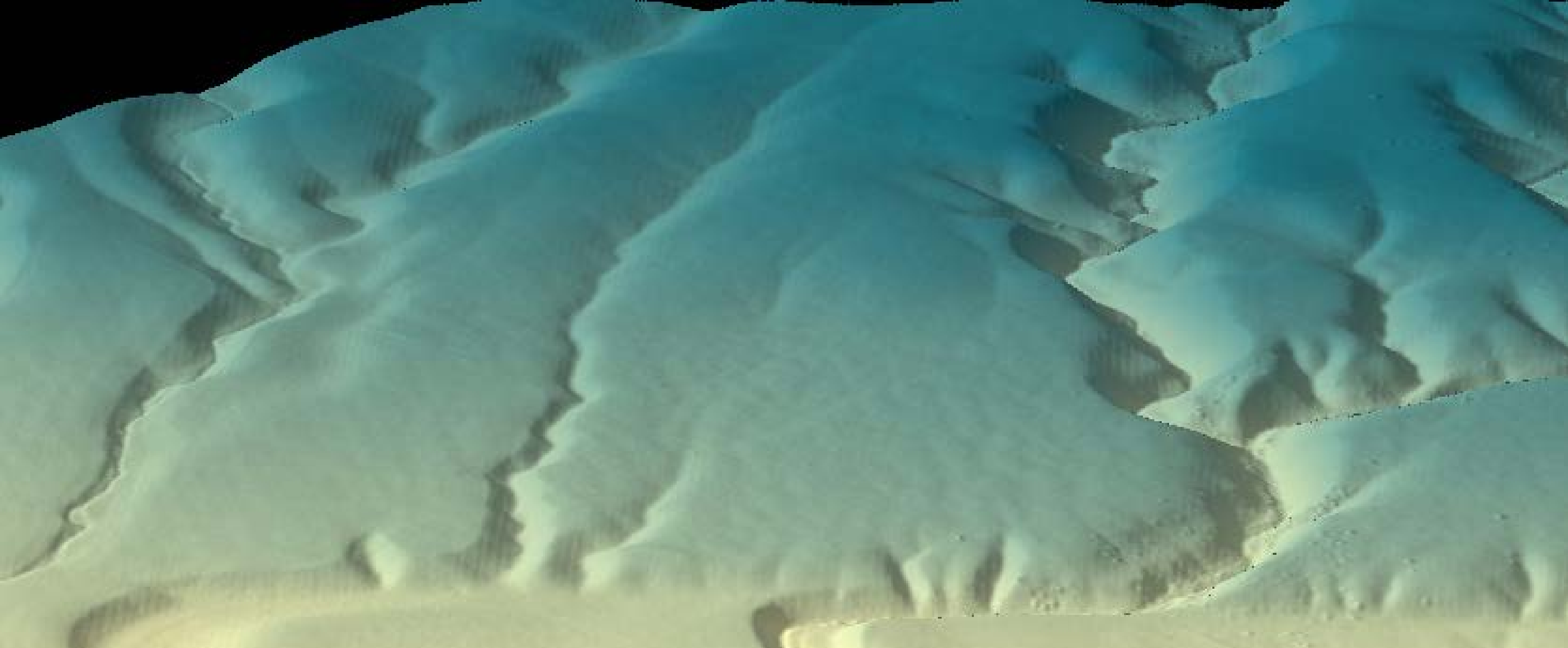


Validation of offset measurements from field and LiDAR data: San Jacinto Fault Clark section

Salisbury et al., 2012


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


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



Outline

- Introduction and LiDAR
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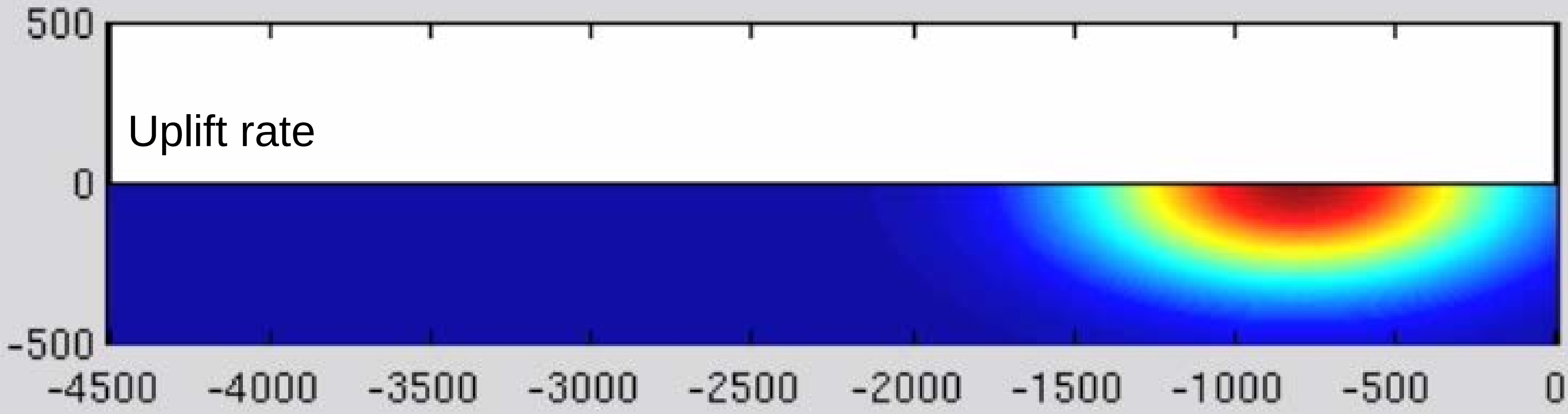
1. Fault trace mapping
2. Reconstructing slip history
3. **Understanding geomorphic response to uplift**
4. Topographic differencing

- Rapid data gathering: Structure from Motion

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

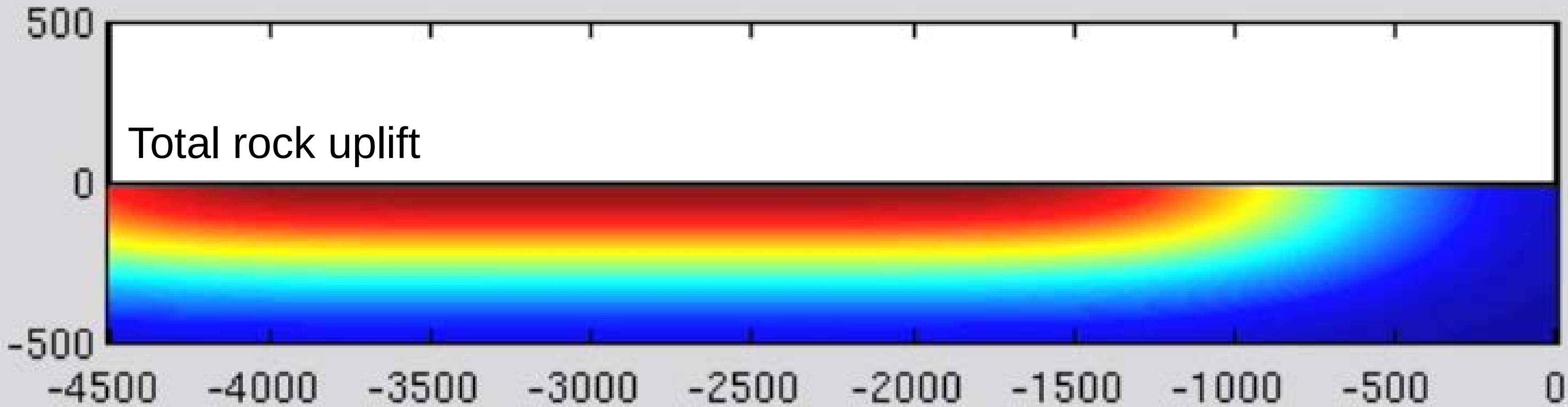
Understanding geomorphic response to uplift



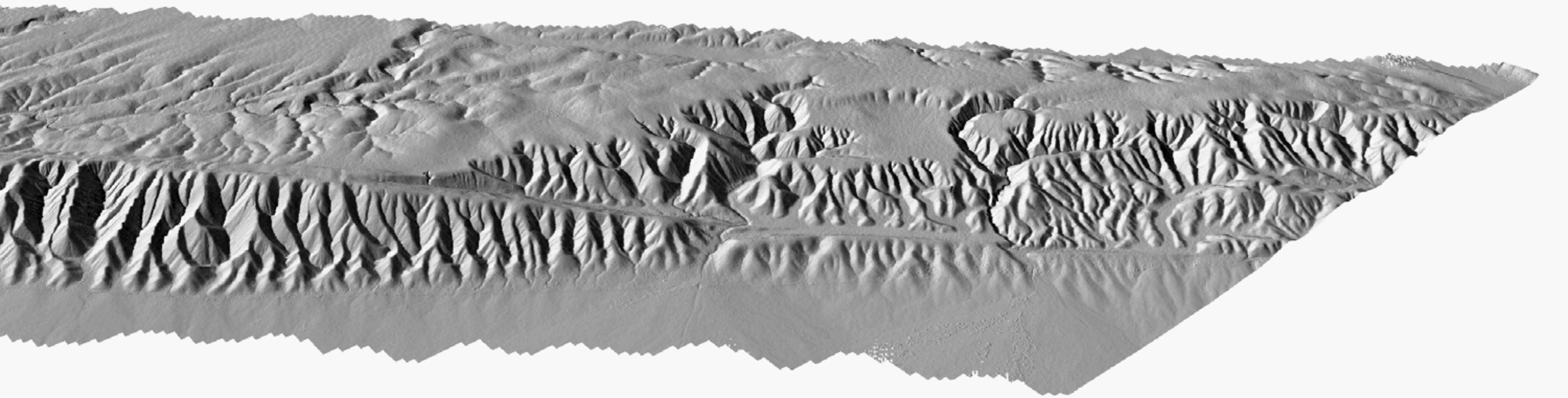
Material moves along fault though relatively stationary uplift zone:

How does landscape respond?

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

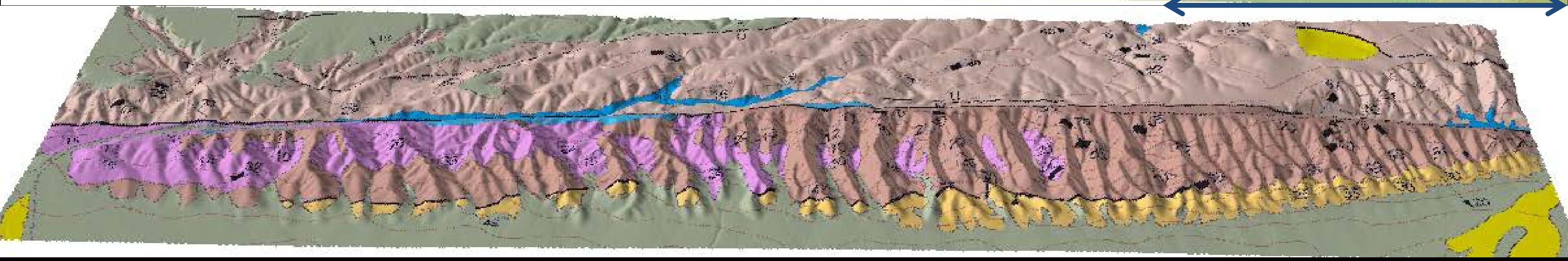


-G. E. Hilley

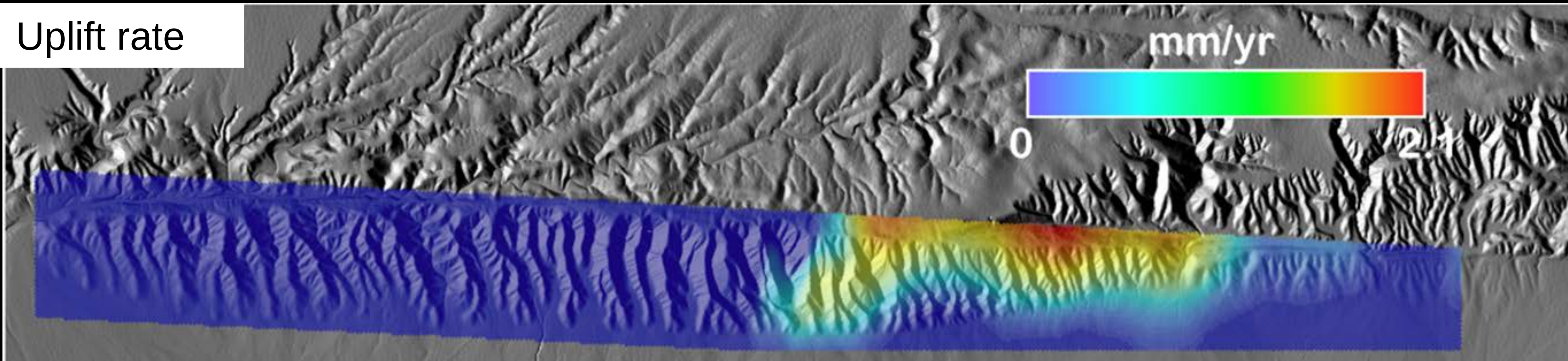


Dragon’s Back Pressure Ridge, Carrizo Plain California

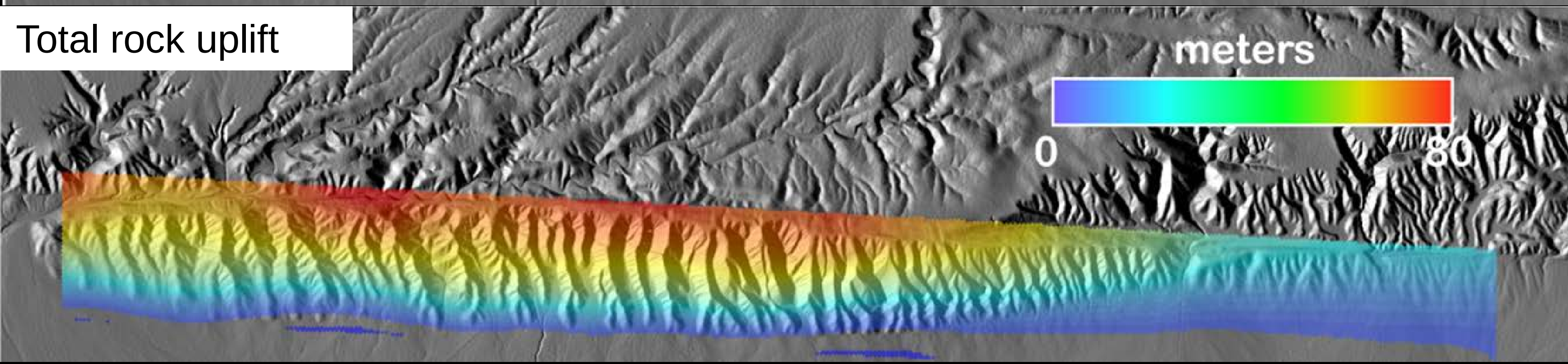
Arrowsmith, 1995; Hilley, 2001; Hilley and Arrowsmith, 2008



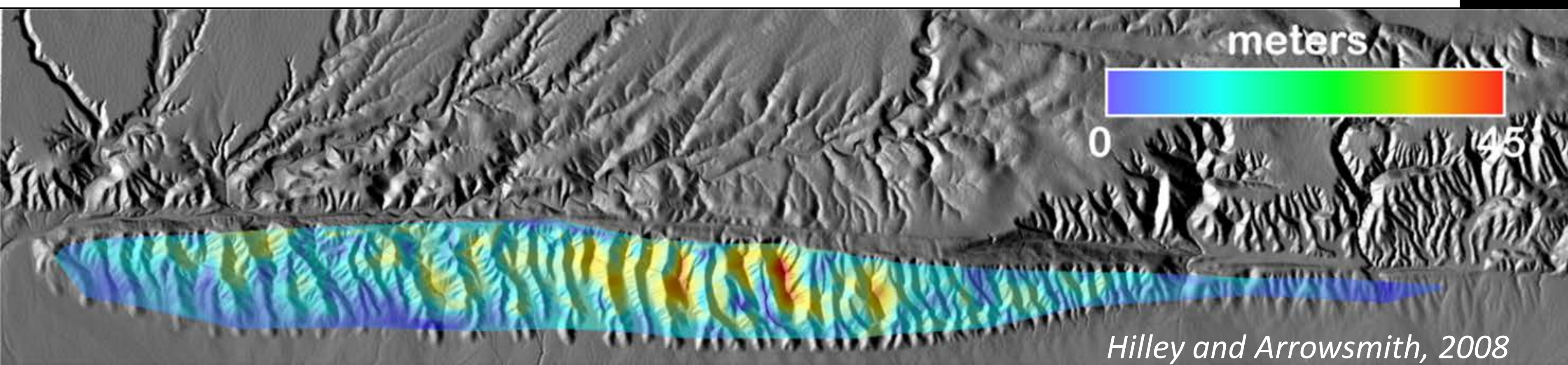
Uplift rate



Total rock uplift



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



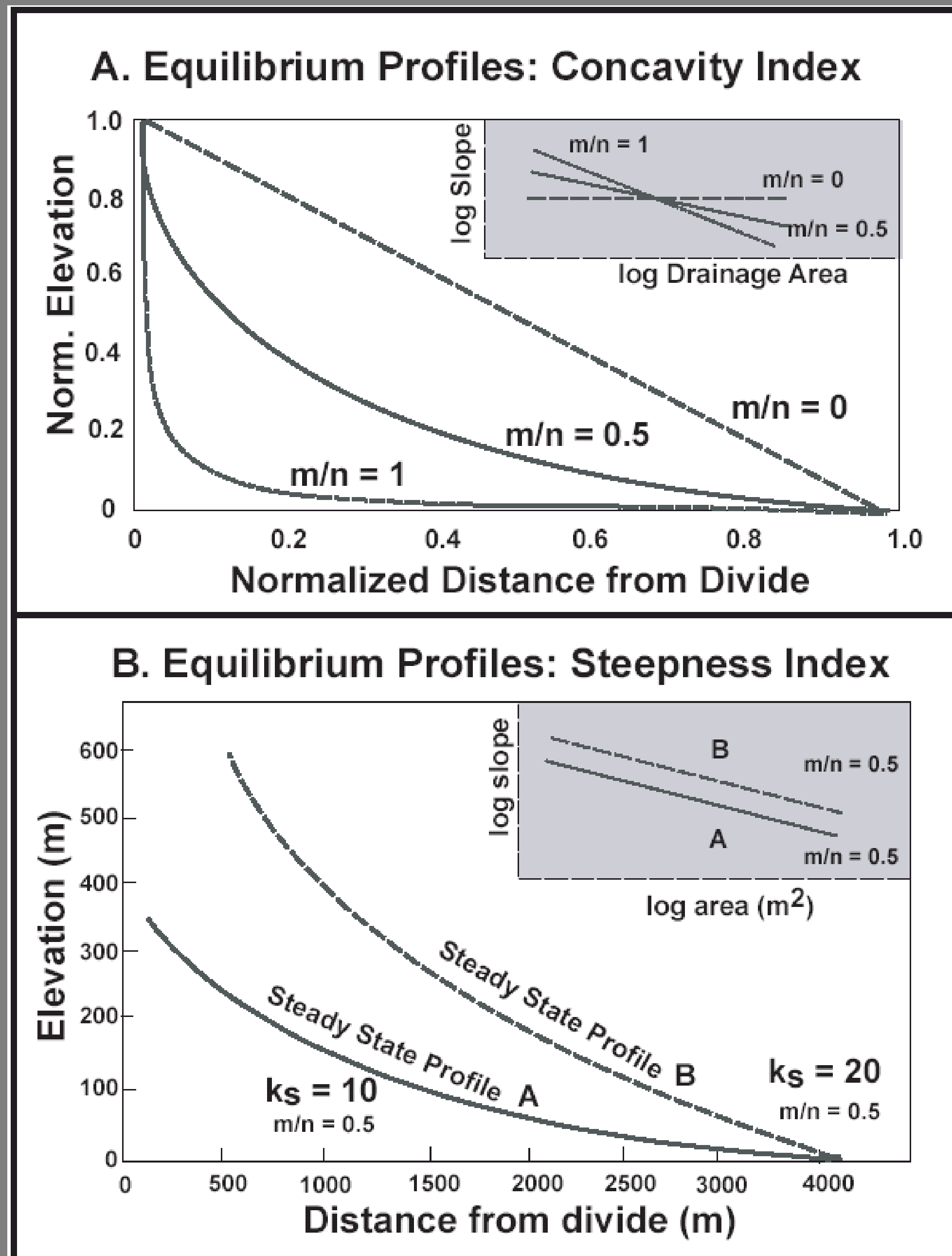
Hilley and Arrowsmith, 2008

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

U = Rock Uplift Rate

Concavity (θ) invariant with U

Steepness (Ks) varies with U

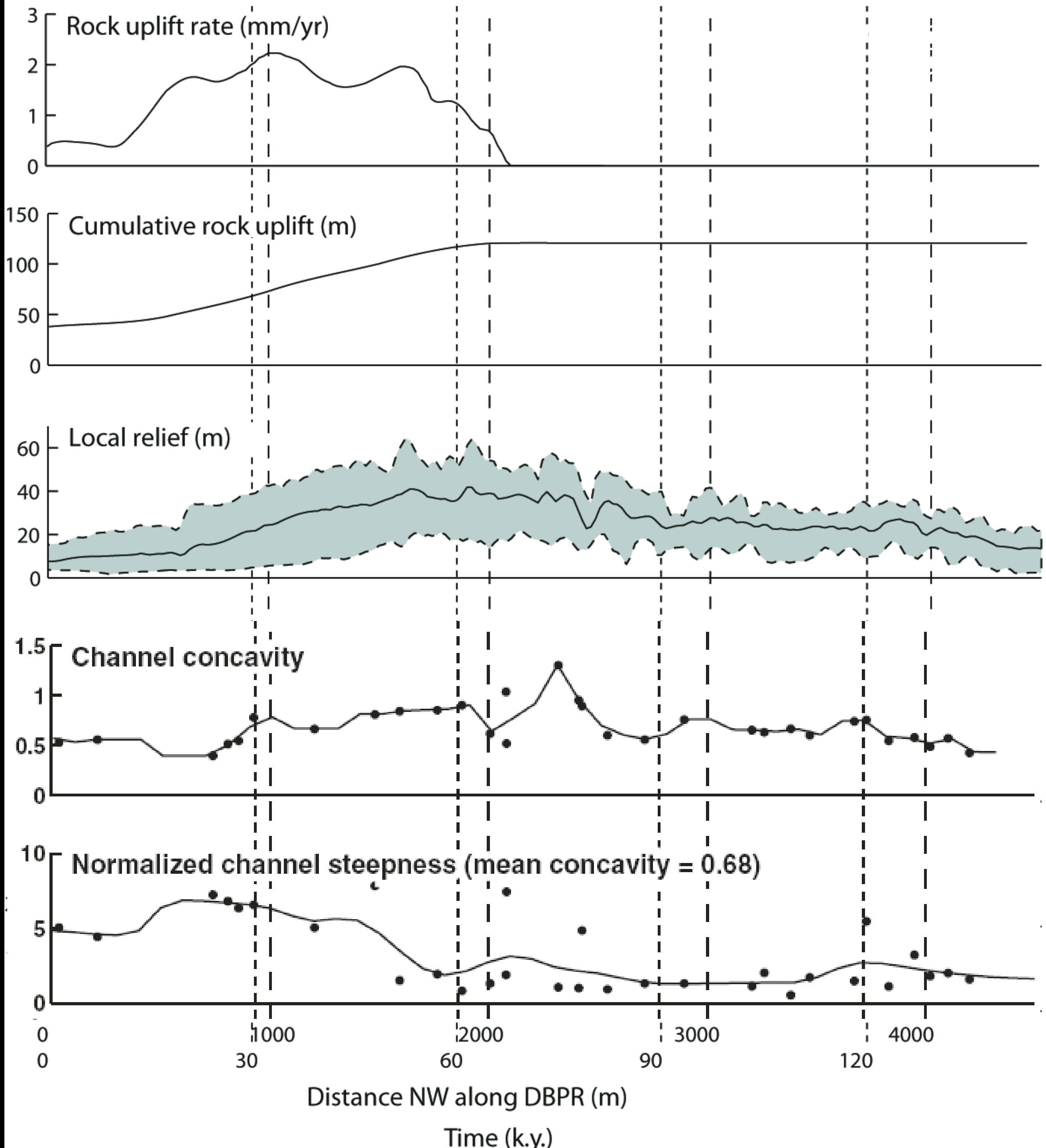


$\theta = m/n$

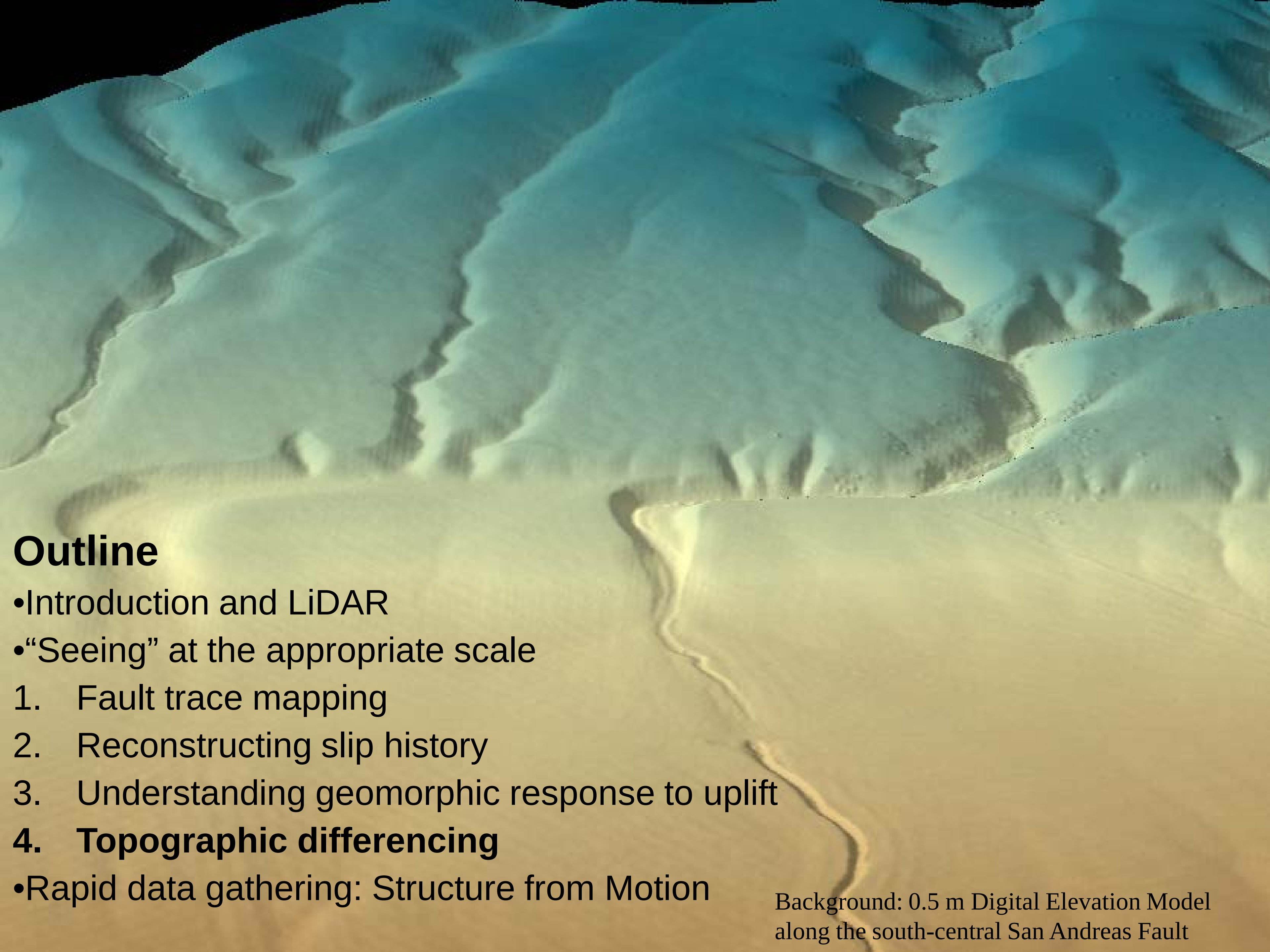
$S = k_s A^{-\theta}$

k_s

--K. X Whipple



Hilley and Arrowsmith, 2008



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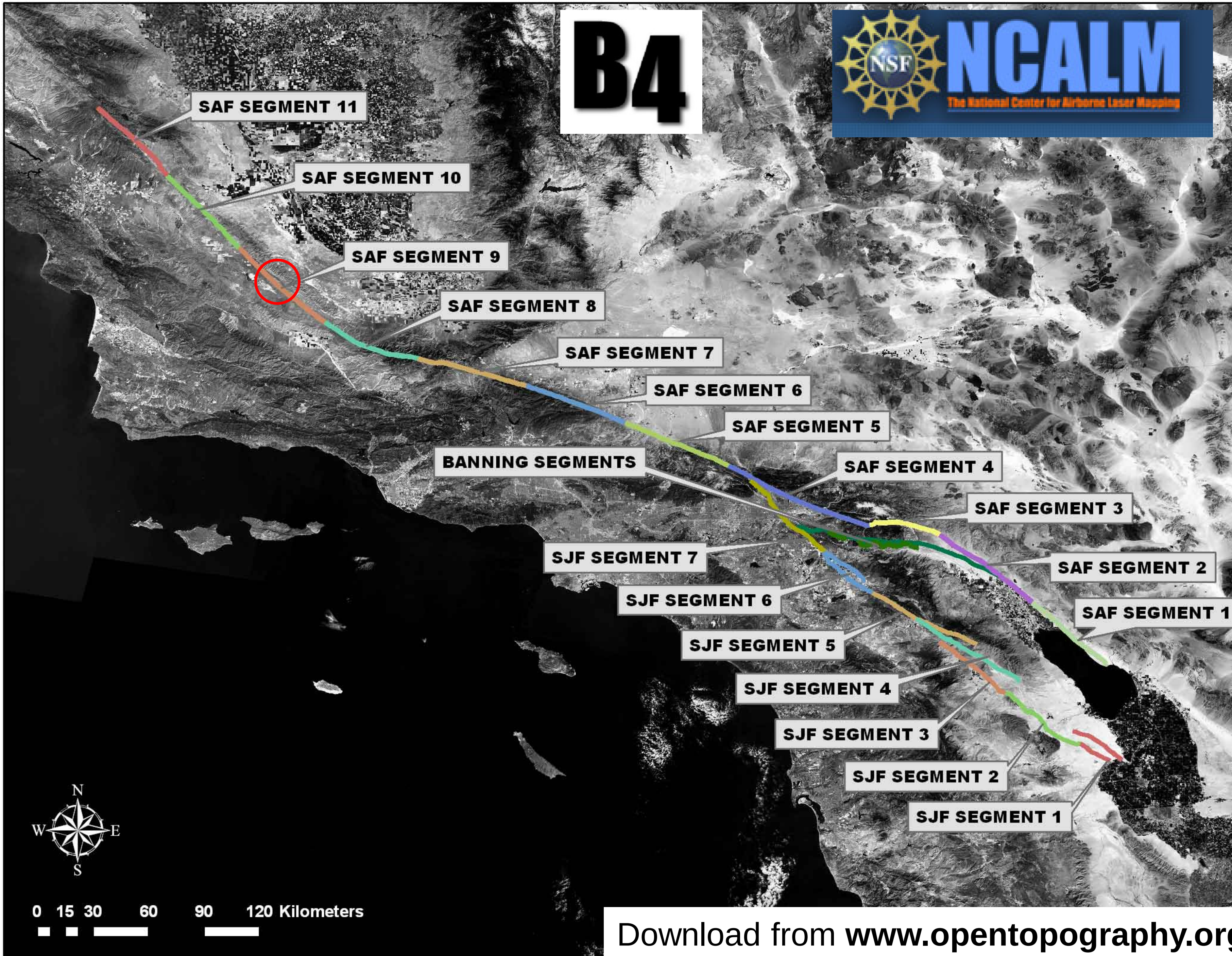
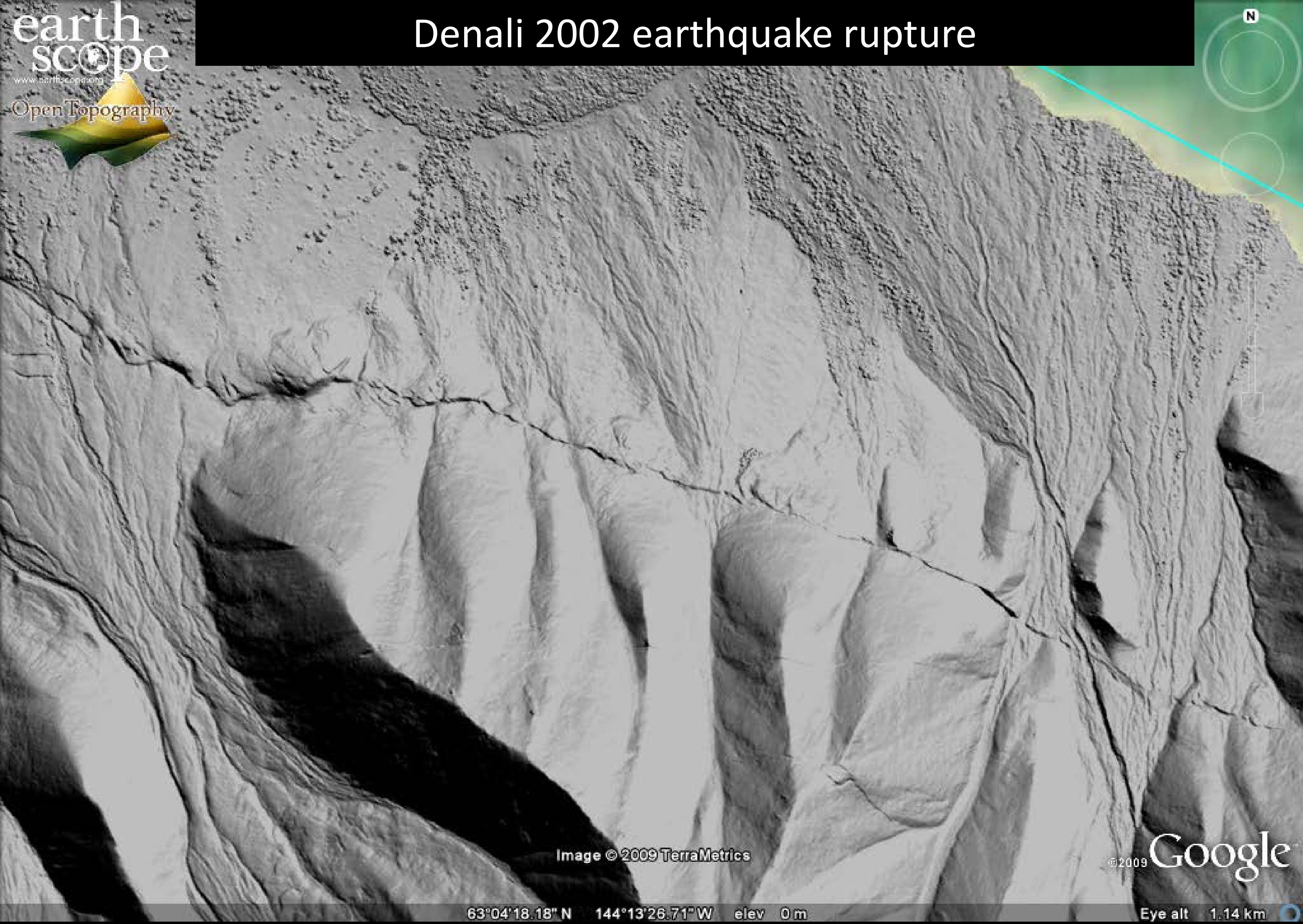
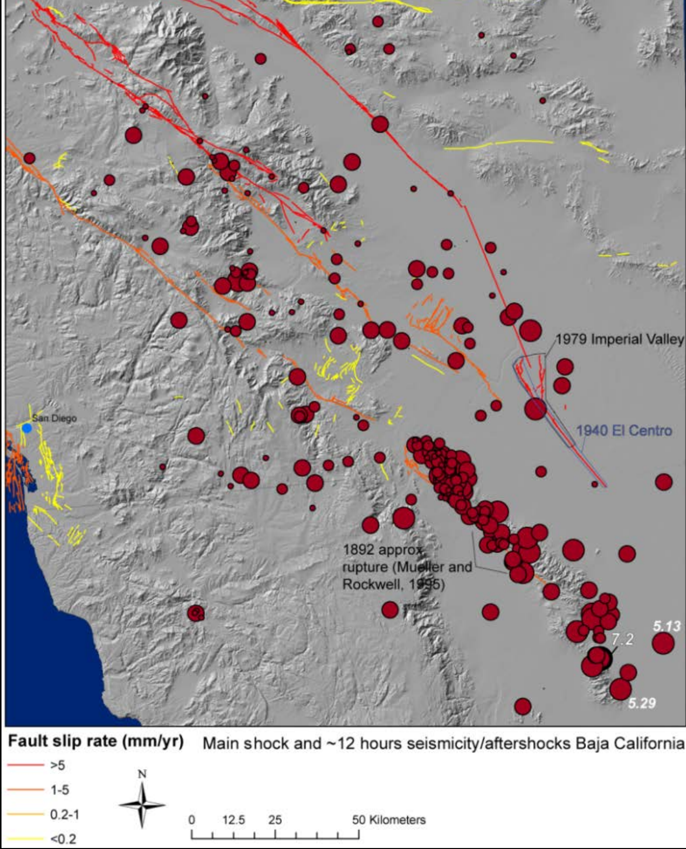
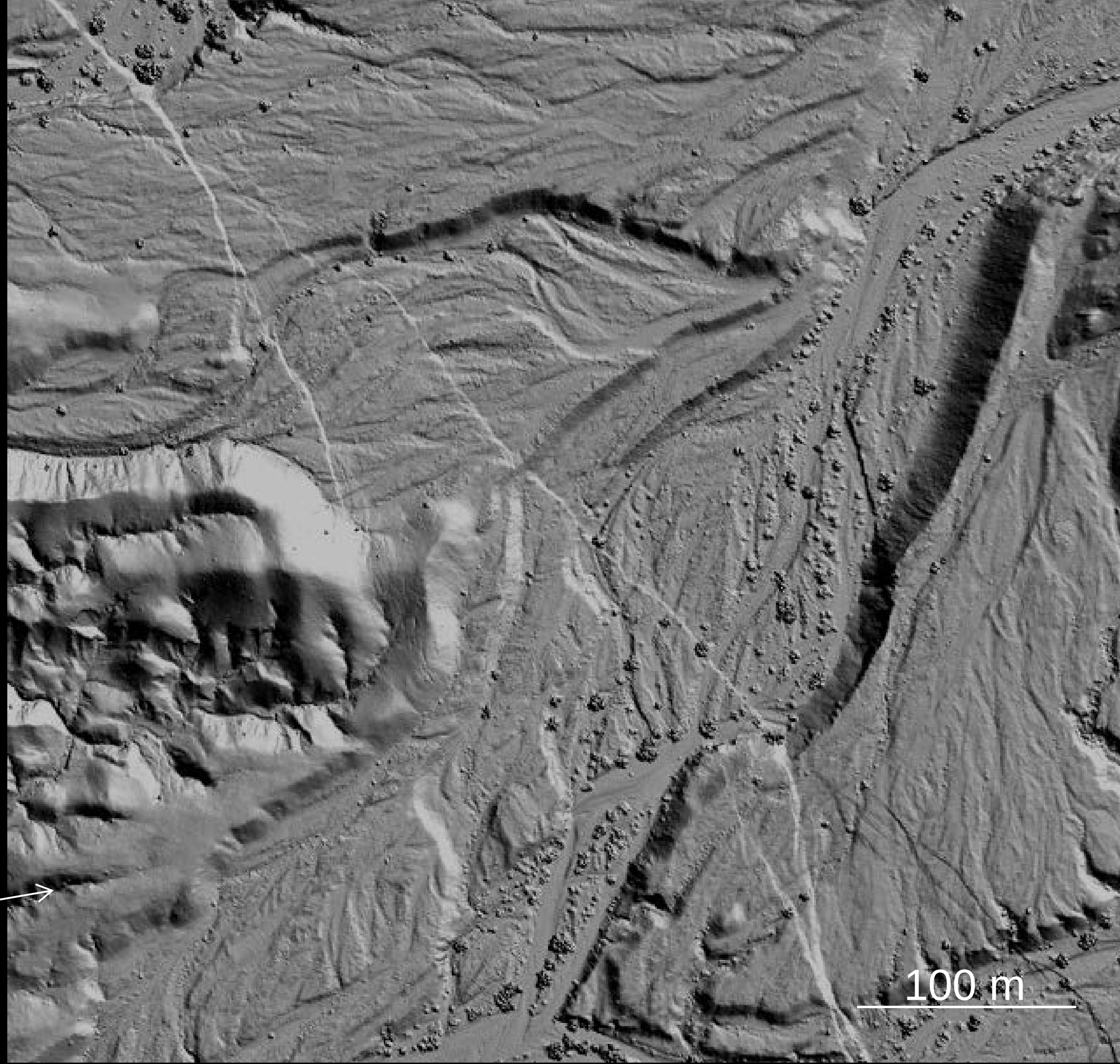

B4
NCALM
NSF
The National Center for Airborne Laser Mapping
SAF SEGMENT 11
SAF SEGMENT 10
SAF SEGMENT 9
SAF SEGMENT 8
SAF SEGMENT 7
SAF SEGMENT 6
SAF SEGMENT 5
BANNING SEGMENTS
SAF SEGMENT 4
SAF SEGMENT 3
SJF SEGMENT 7
SAF SEGMENT 2
SJF SEGMENT 6
SAF SEGMENT 1
SJF SEGMENT 5
SJF SEGMENT 4
SJF SEGMENT 3
SJF SEGMENT 2
SJF SEGMENT 1
N
W
E
S
0 15 30 60 90 120 Kilometers

Denali 2002 earthquake rupture



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





El Mayor Cucupah earthquake rupture laser scan

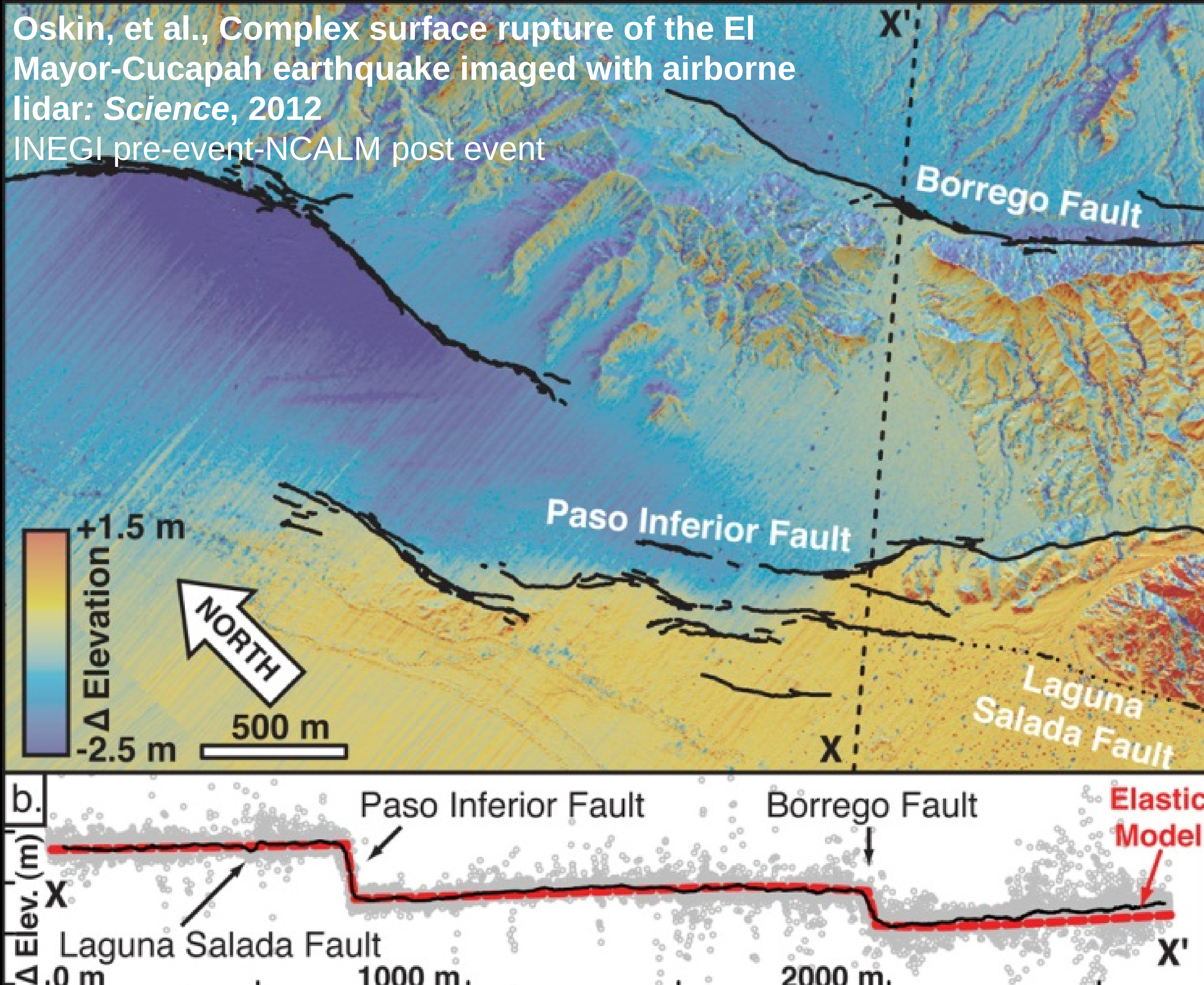
Oskin, et al., in review

UC DAVIS DEPARTMENT of GEOLOGY
CICESE
ASU School of Earth & Space Exploration ARIZONA STATE UNIVERSITY
NSF NCALM


Photo by Tom Rockwell

Oskin, et al., Complex surface rupture of the El Mayor-Cucapah earthquake imaged with airborne lidar*: Science*, 2012

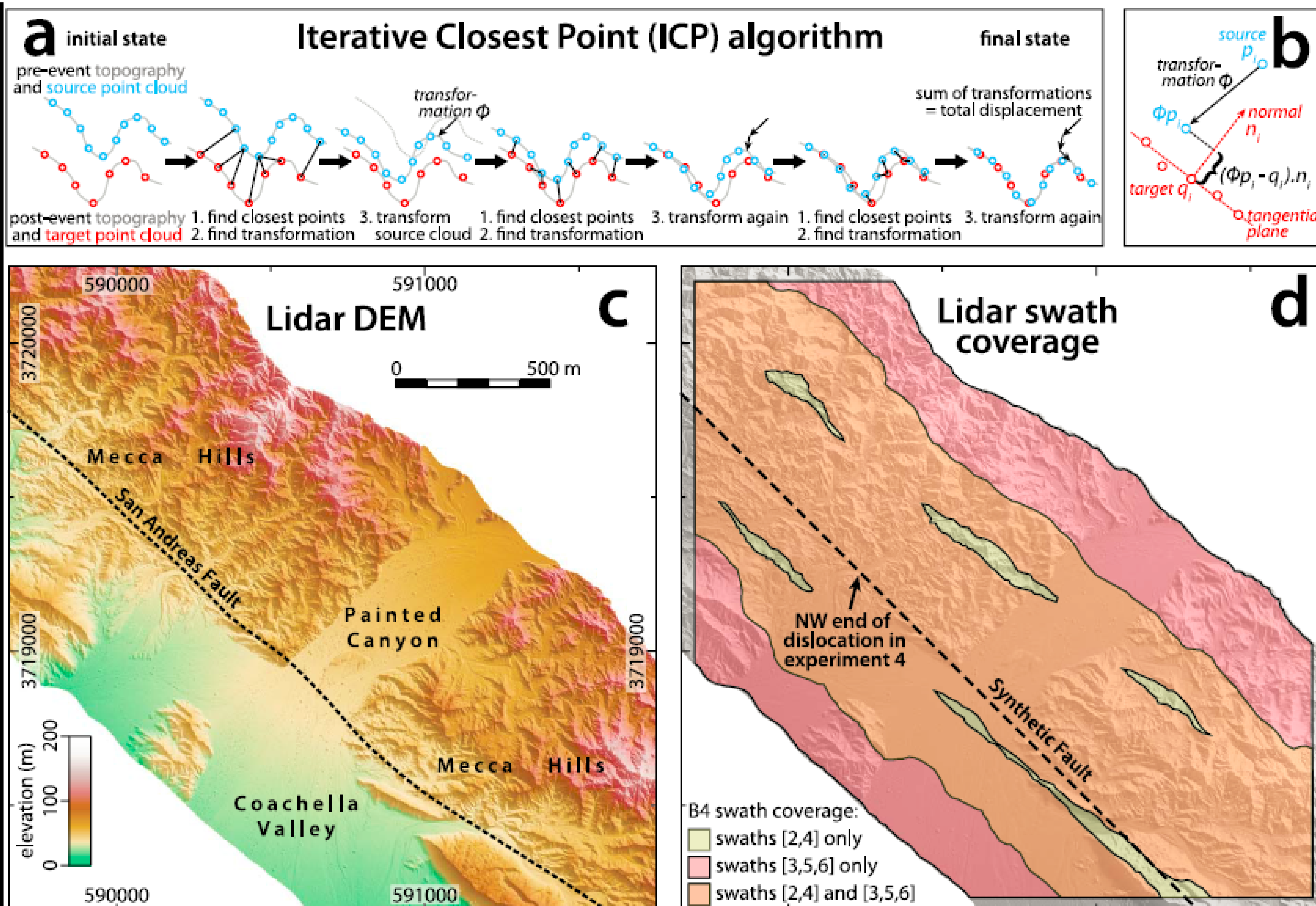
INEGI pre-event-NCALM post event

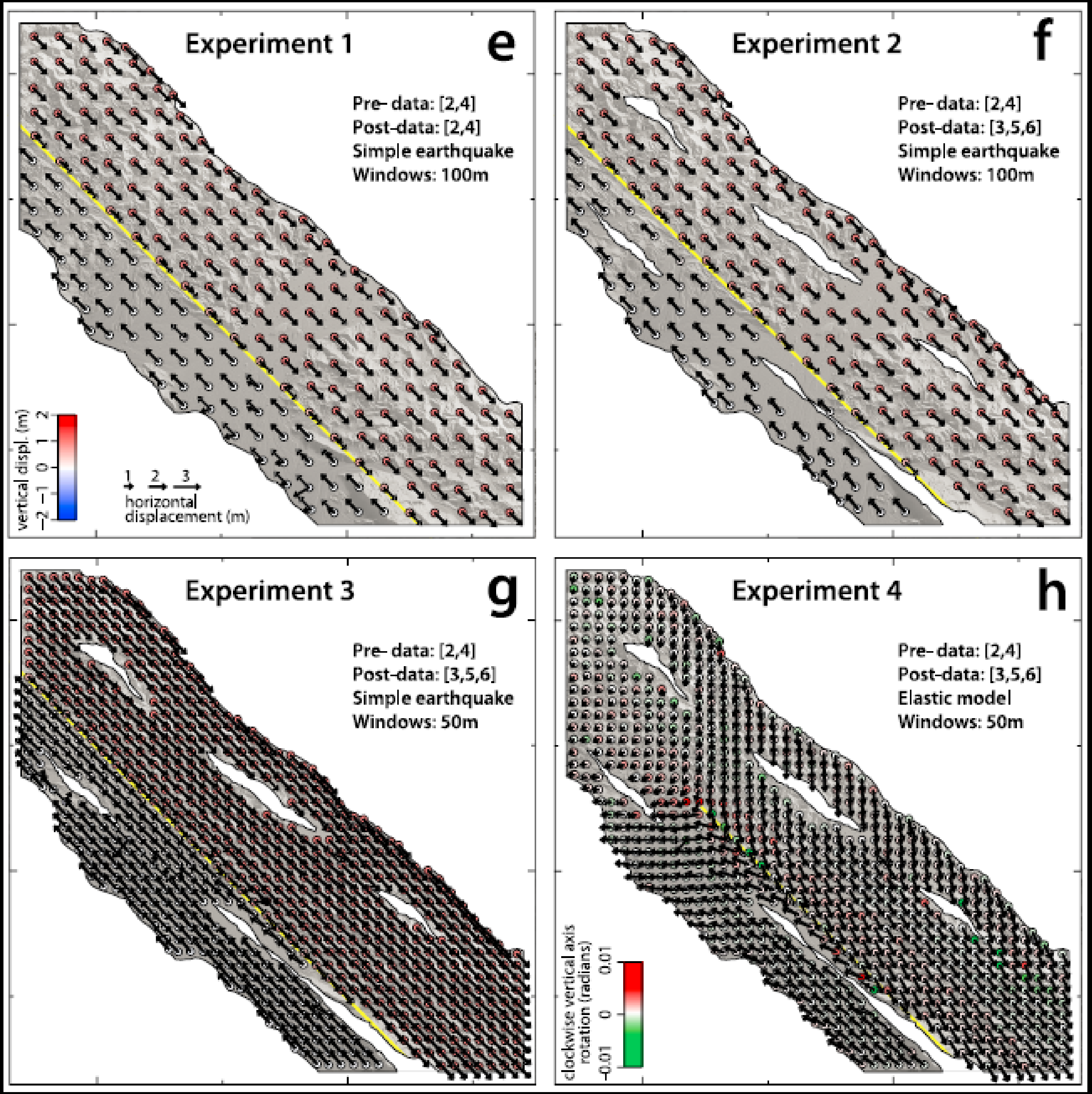


Three-dimensional surface displacements and rotations from differencing pre- and post-earthquake LiDAR point clouds

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

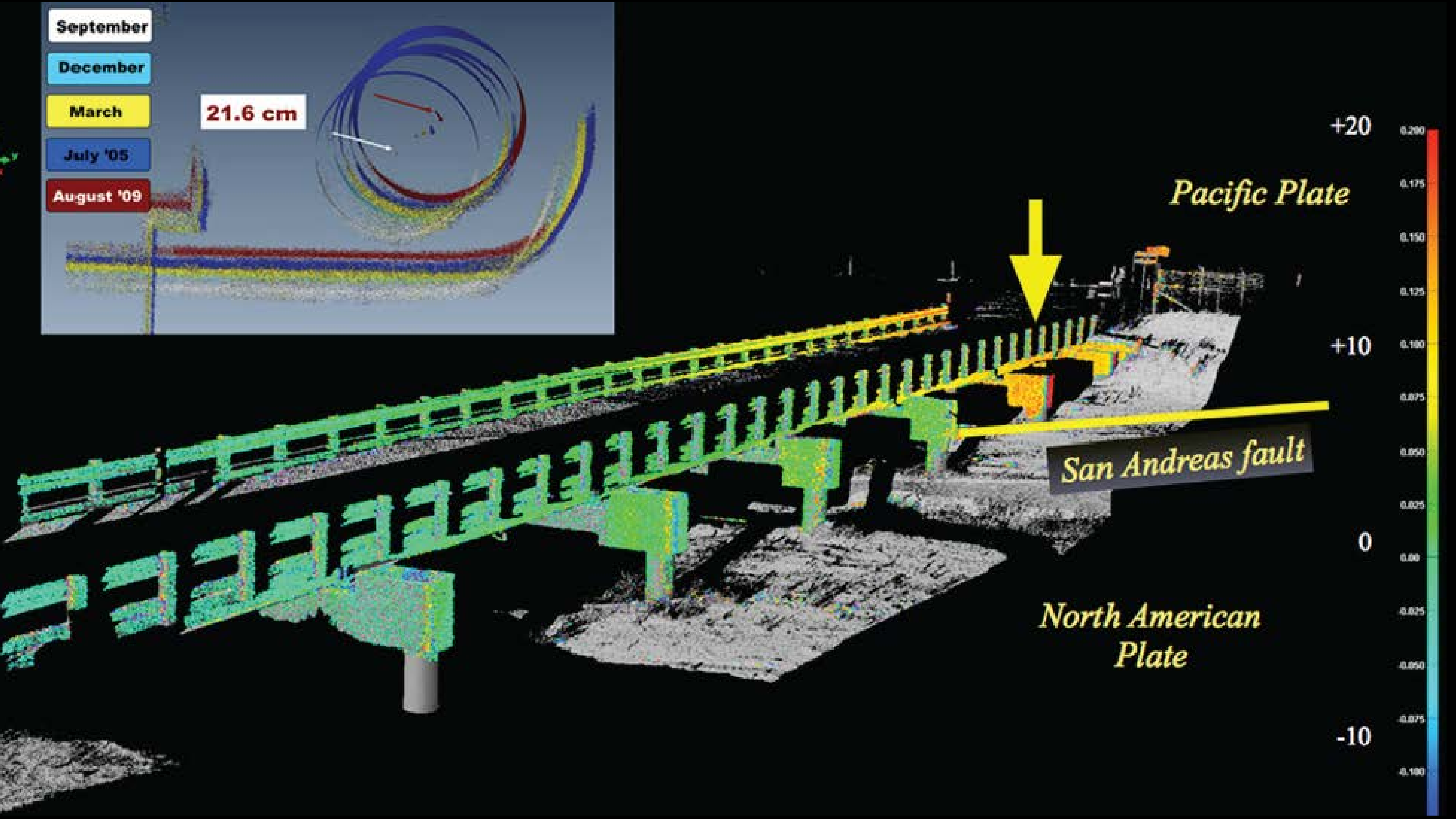
Edwin Nissen,[1,2] Aravindhan K. Krishnan,[1] J. Ramón Arrowsmith,[1] and Srikanth Saripalli[1]



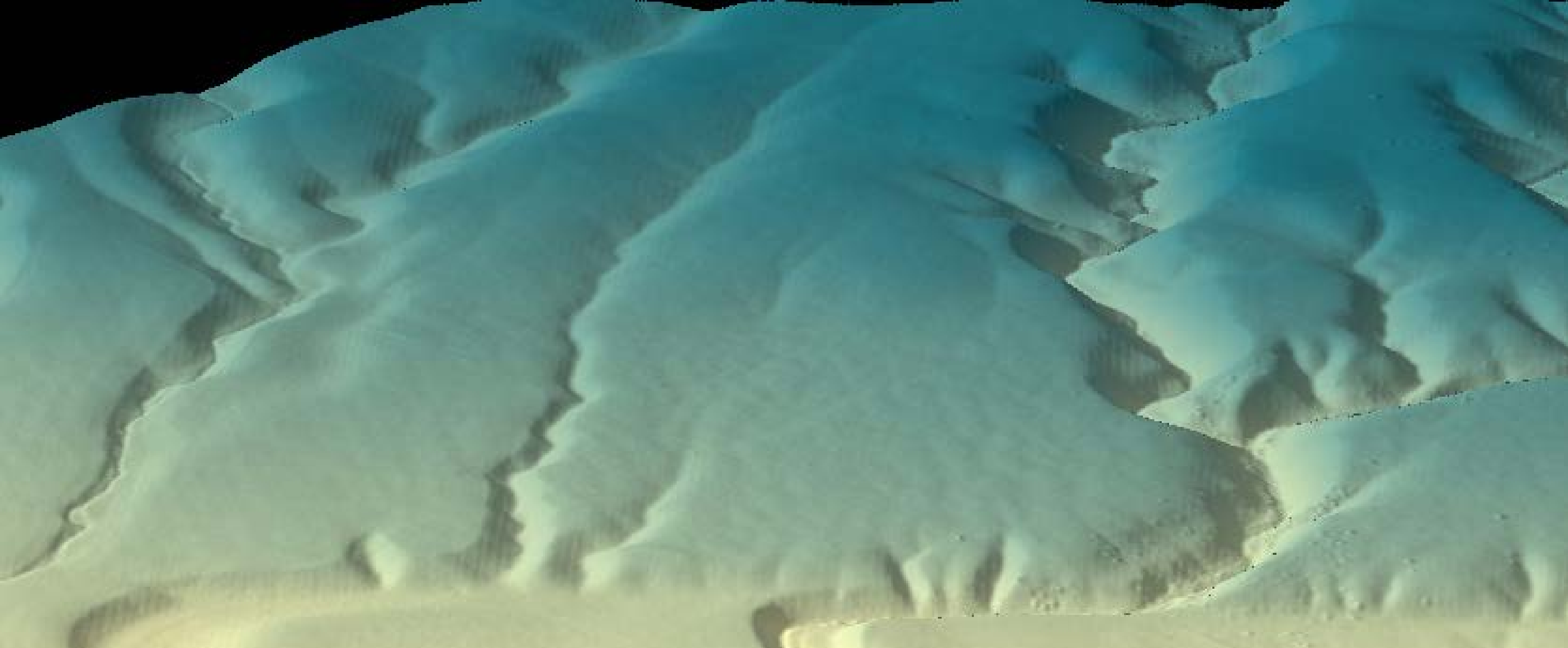


Experiment 1
e
Pre- data: [2,4]
Post-data: [2,4]
Simple earthquake
Windows: 100m
vertical displ. (m)
2
1
0
−1
−2
1 2 3
horizontal displacement (m)
Experiment 2
f
Pre- data: [2,4]
Post-data: [3,5,6]
Simple earthquake
Windows: 100m
Experiment 3
g
Pre- data: [2,4]
Post-data: [3,5,6]
Simple earthquake
Windows: 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



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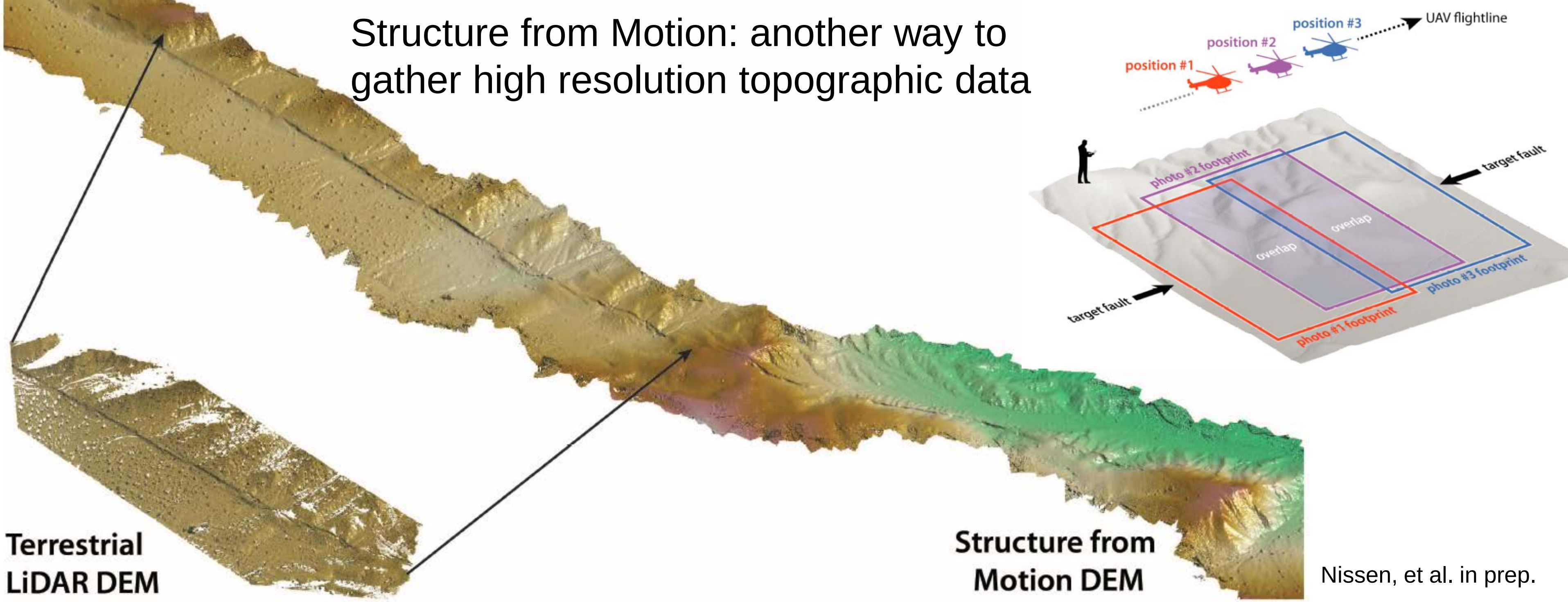
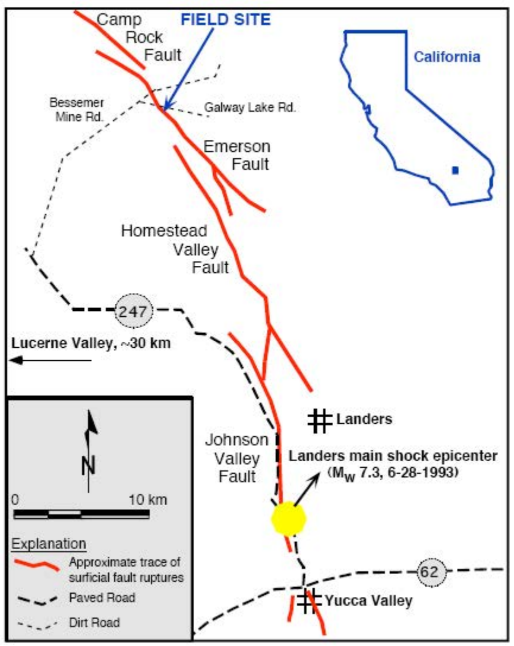
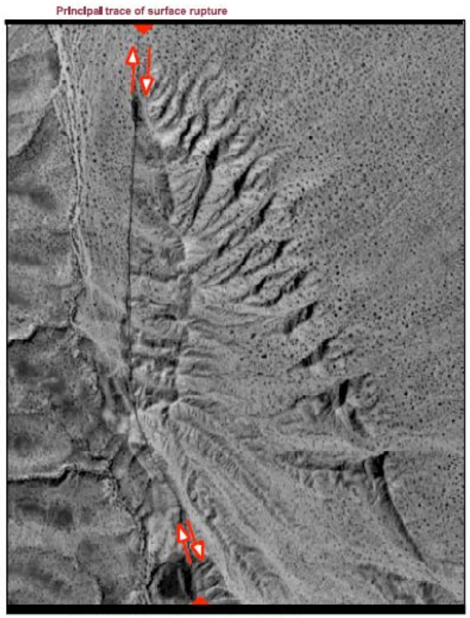
Structure from Motion: another way to gather high resolution topographic data



Nissen, et al. in prep.





6-30-1992: U S Geological Survey

Structure from Motion: another way to gather high resolution topographic data

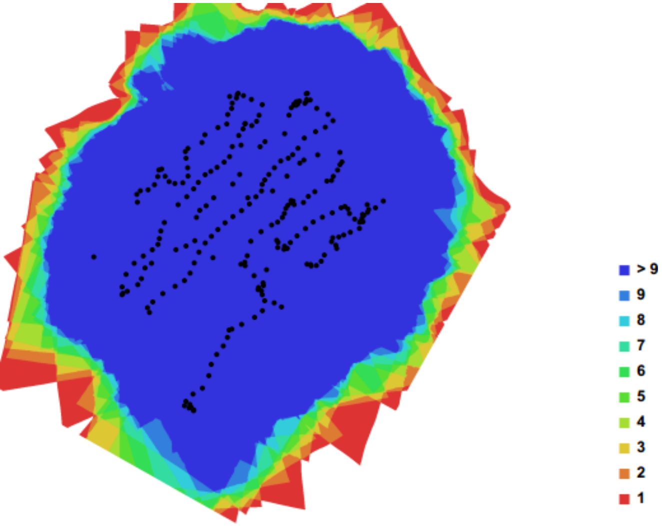
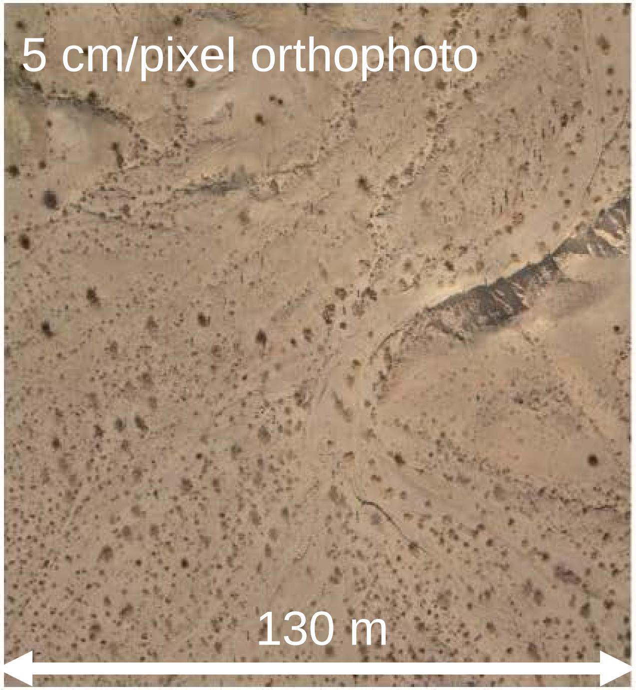
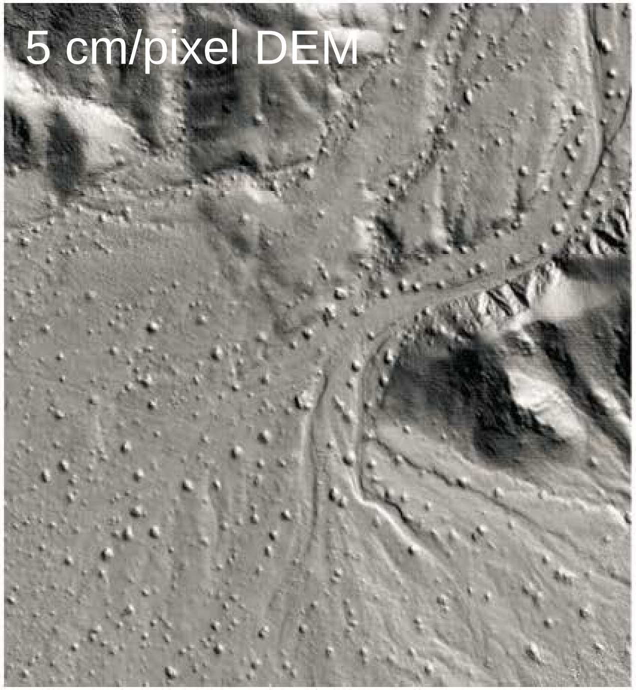
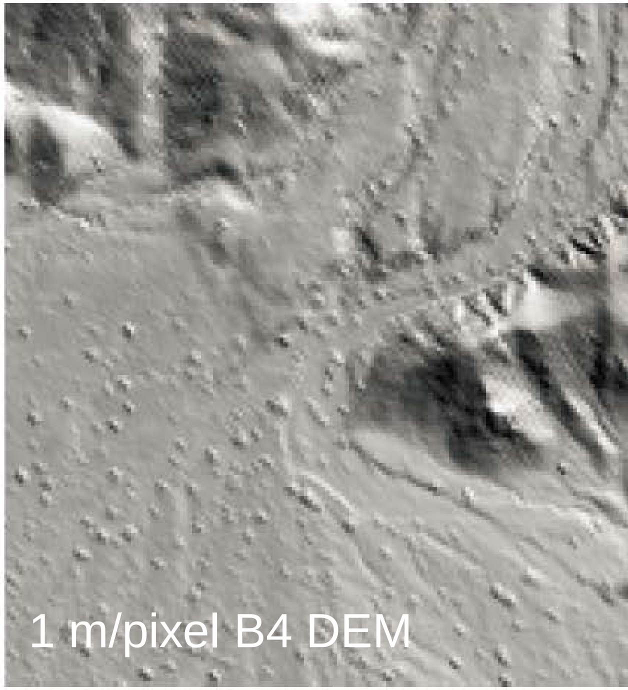


Fig. 1. Camera locations and image overlap.

Nissen, et al. in prep.







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