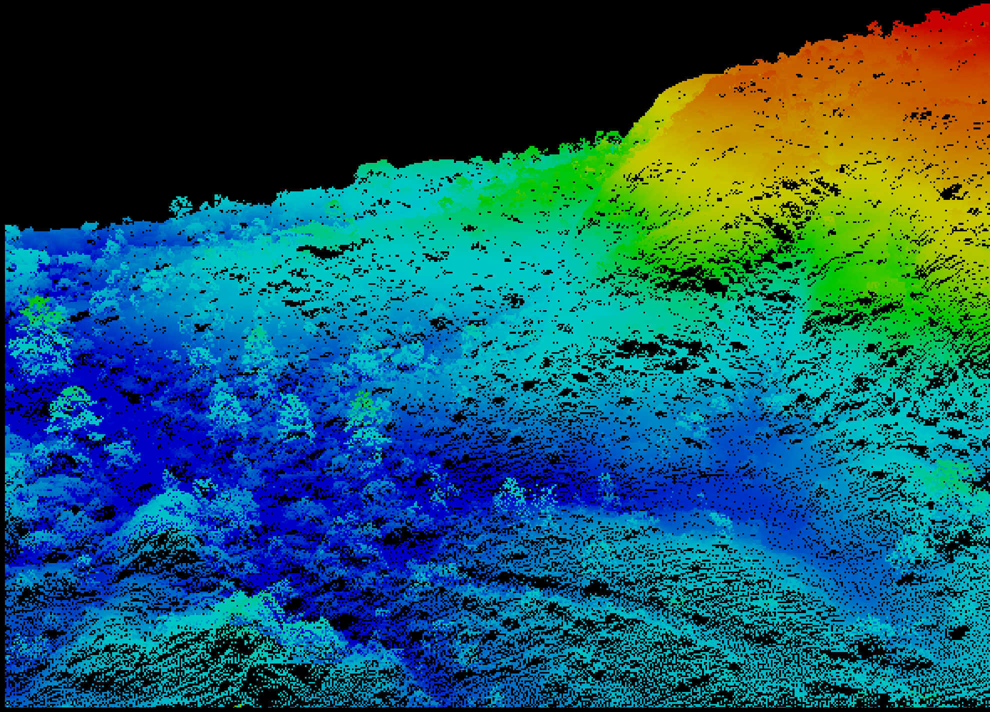
Sharpening our view of earth processes with high resolution topography

Denali 2002 earthquake rupture (EarthScope)



Granite Dells AZ point cloud (NCALM student seed grant)

Presentation outline

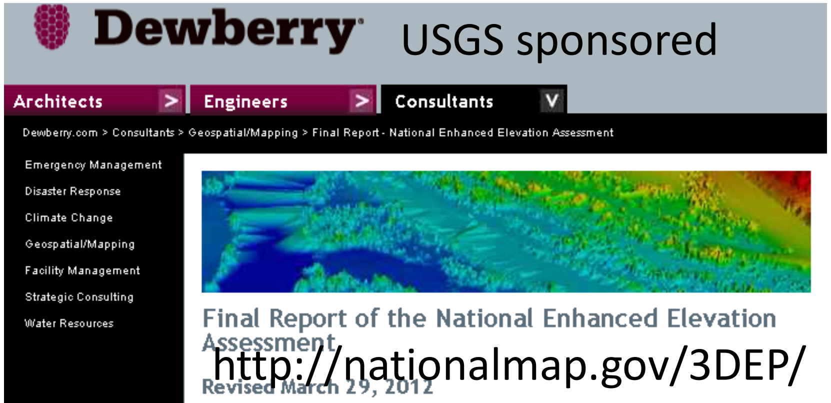
- **Introduction and measuring topography**
- “Seeing” and working at the appropriate scale
- Applications

Main Application types

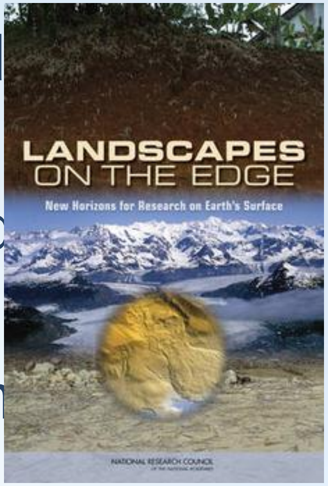
- Feature mapping at fine scale
- Landscape reconstruction (offsets)
- Surface process interactions with tectonic processes
- Differencing of repeat surveys

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

Science communities

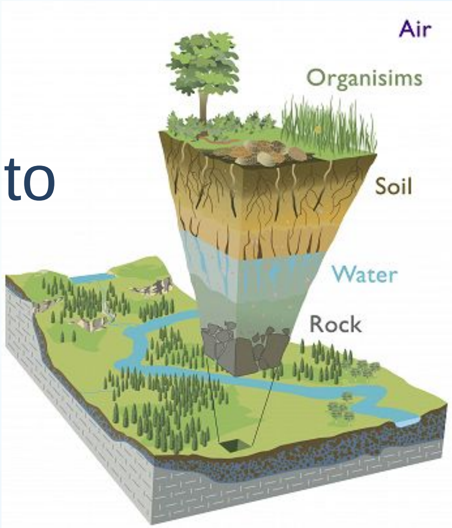


Example scientific motivations



- 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?

- How does the landscape record evidence of prior earthquakes?



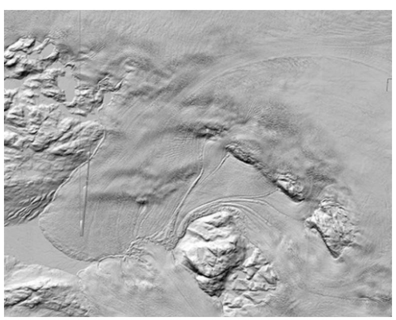
- Coupled hydrogeomorphic-ecosystem response to natural and anthropogenic change
- Landscape and ecosystem dynamics

- Volcano form and process
- Changes in volume of domes, edifice, flows over time

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

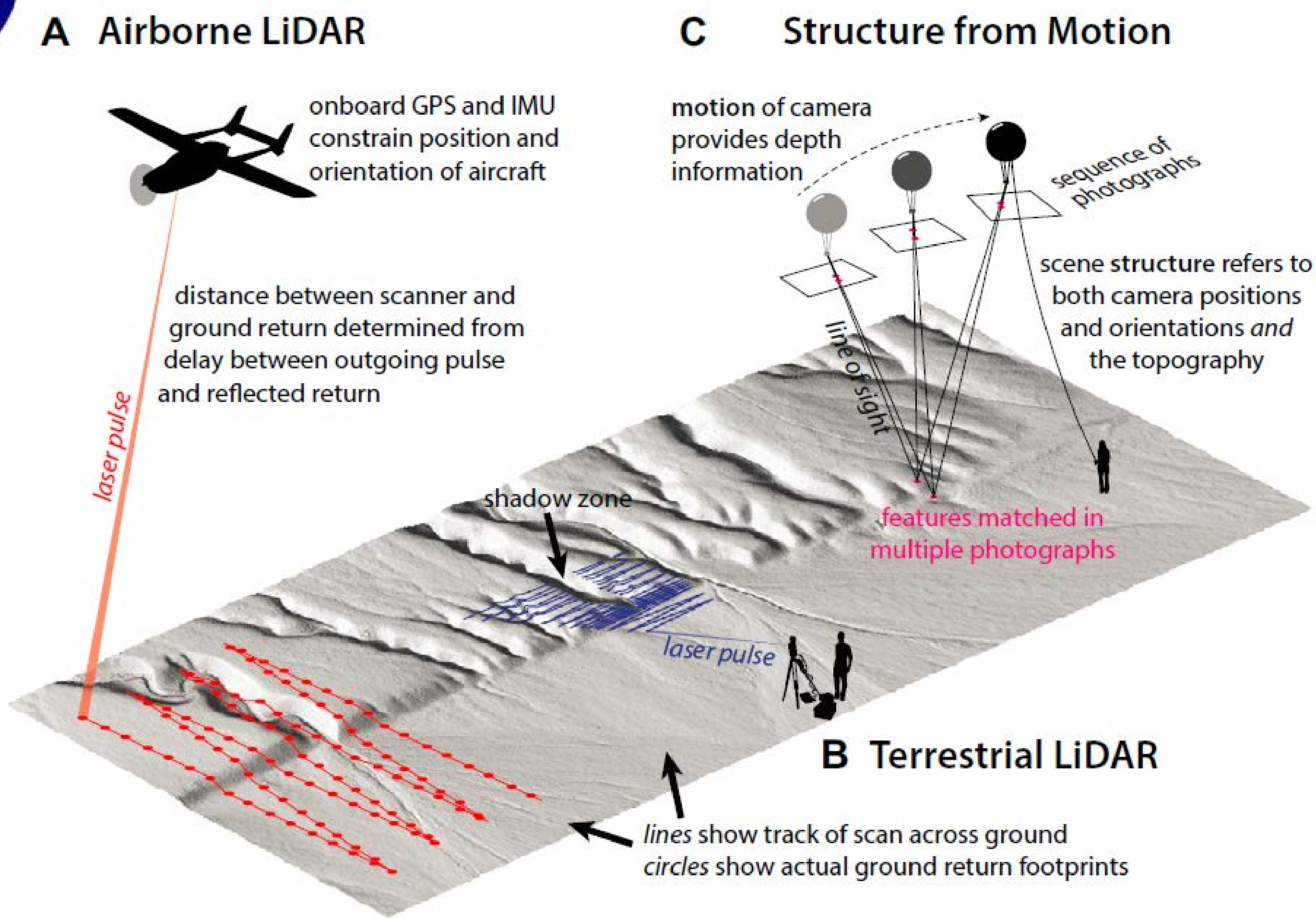
Global and regional topography/bathy (10s-100s m/pix)

+ASTER



Stereo-Photogrammetric Elevation Model (Polar Geospatial Center)

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



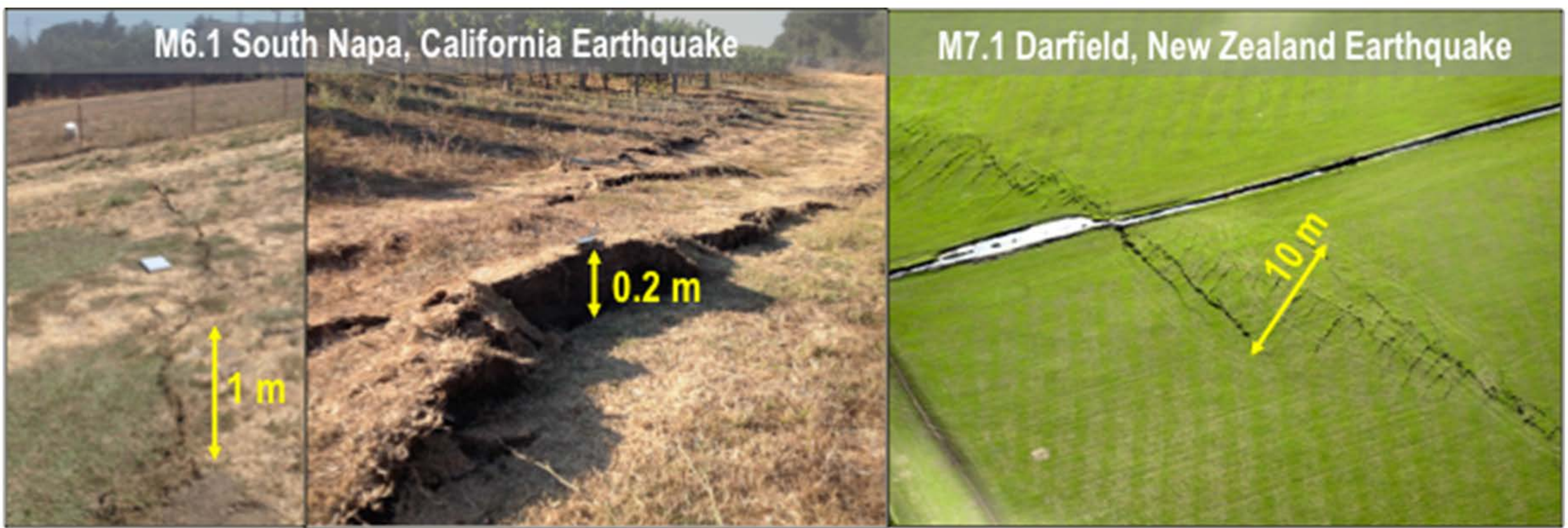
Johnson, K., Nissen, E., Saripalli, S., Arrowsmith, J R., McGarey, P., Scharer, K., Williams, P., Blisniuk, K., Rapid mapping of ultra-fine fault zone topography with Structure from Motion, Geosphere, v. 10; no. 5; p. 1–18; doi:10.1130/GES01017.1, 2014.

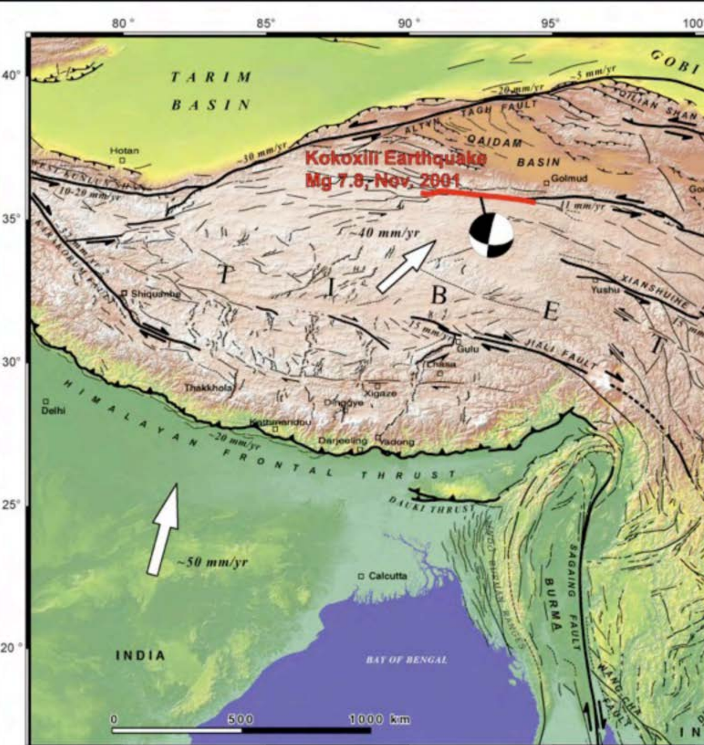
Presentation outline

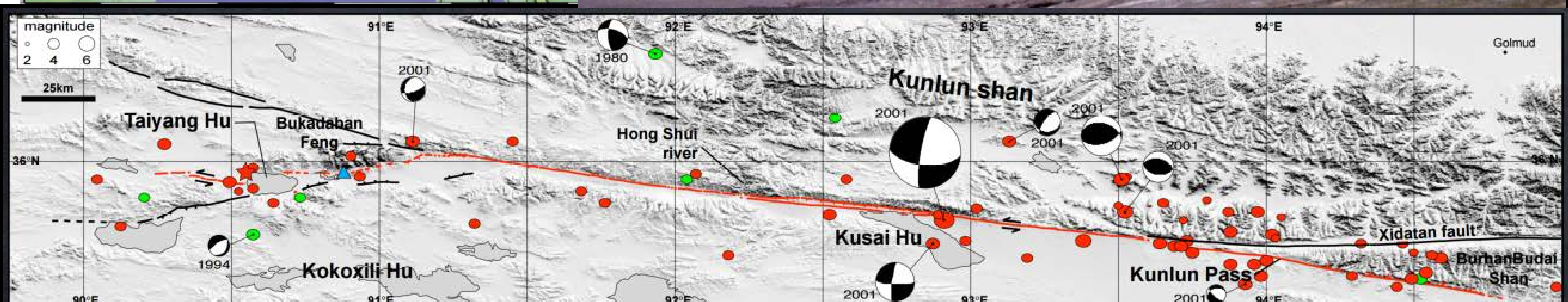
- Introduction and measuring topography
- **“Seeing” and working at the appropriate scale**
- Applications

Science requirements

- Need topography data with sufficient spatial extent and resolution to capture phenomena of interest
- Need topography data with sufficient temporal repeat to capture changes of interest





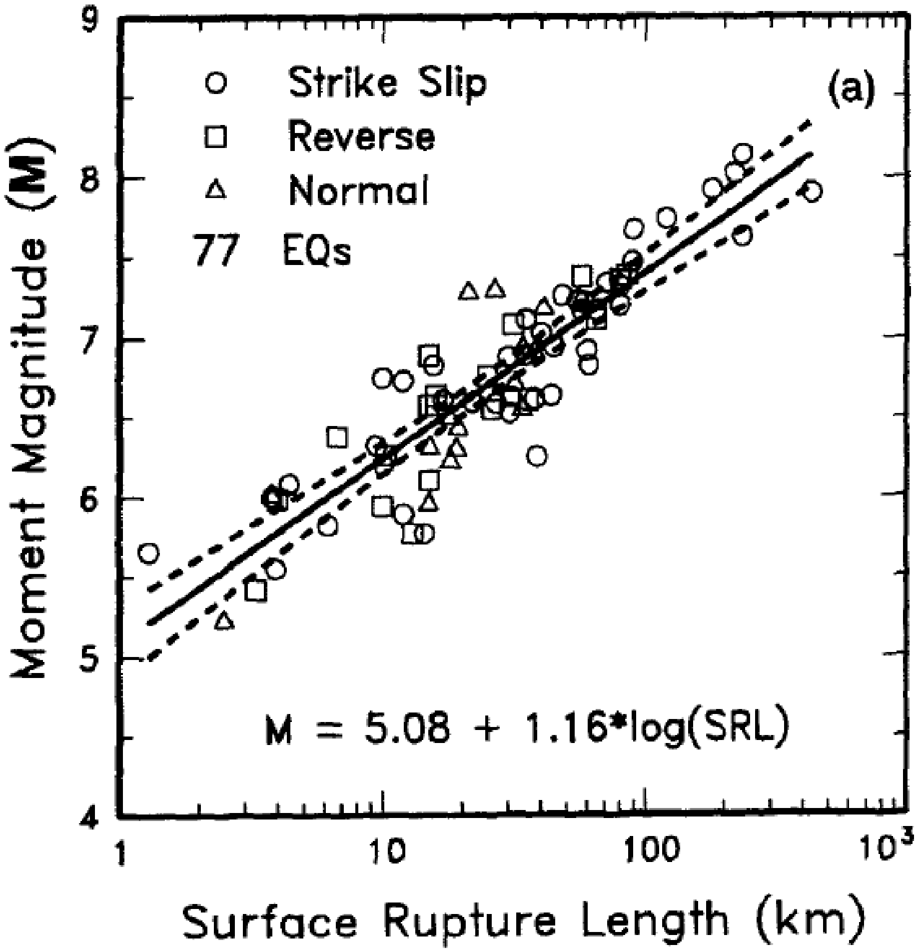


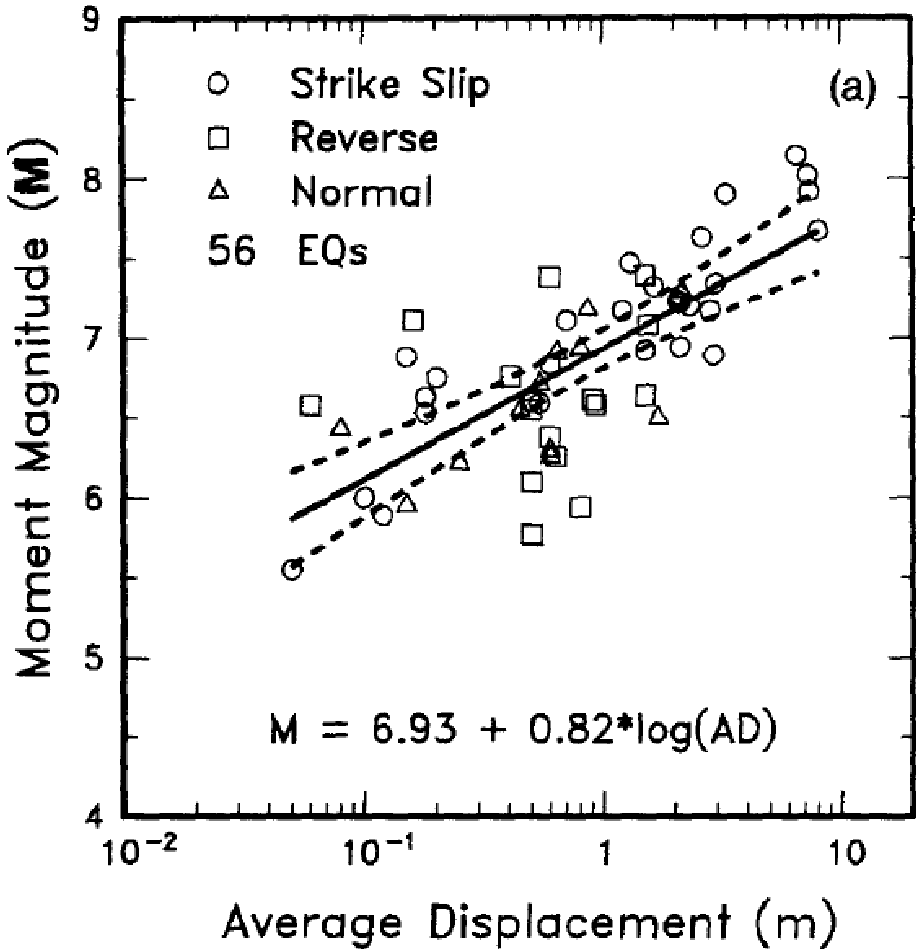
430km of ground rupture, above 4000m

Yann Klinger, IPGP;
http://peer.berkeley.edu/events/2009/sfdc_workshop/Klinger_Kunlun_EQ.pdf

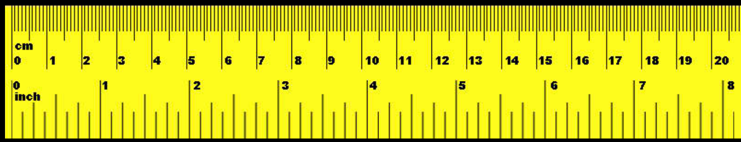
Length scales >10^5m and <1 m

Wells and Coppersmith, 1994





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



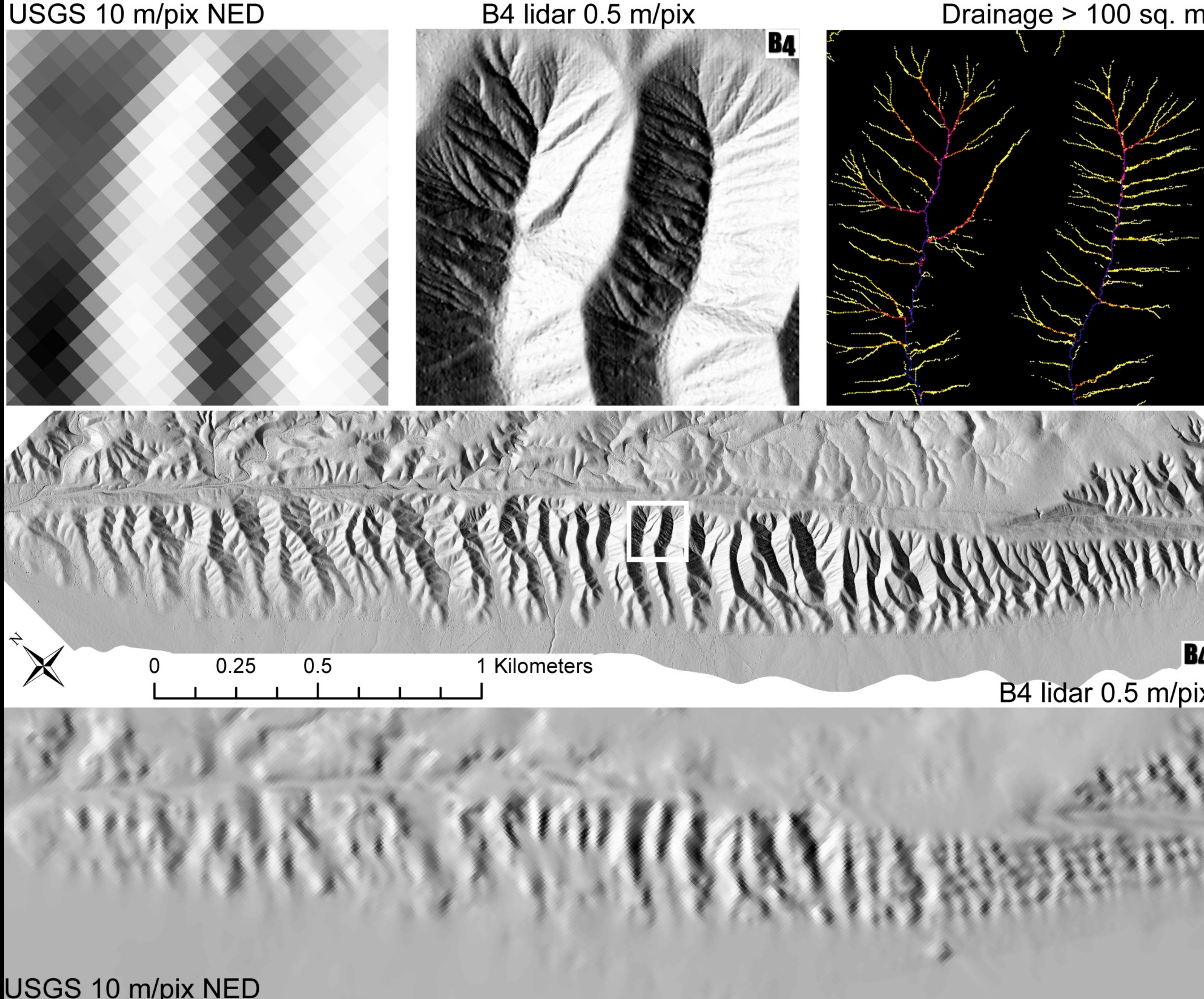
Surface processes act to change elevation through erosion and deposition while tectonic processes depress or elevate the surface directly— their record is best characterized with the right fine scale.

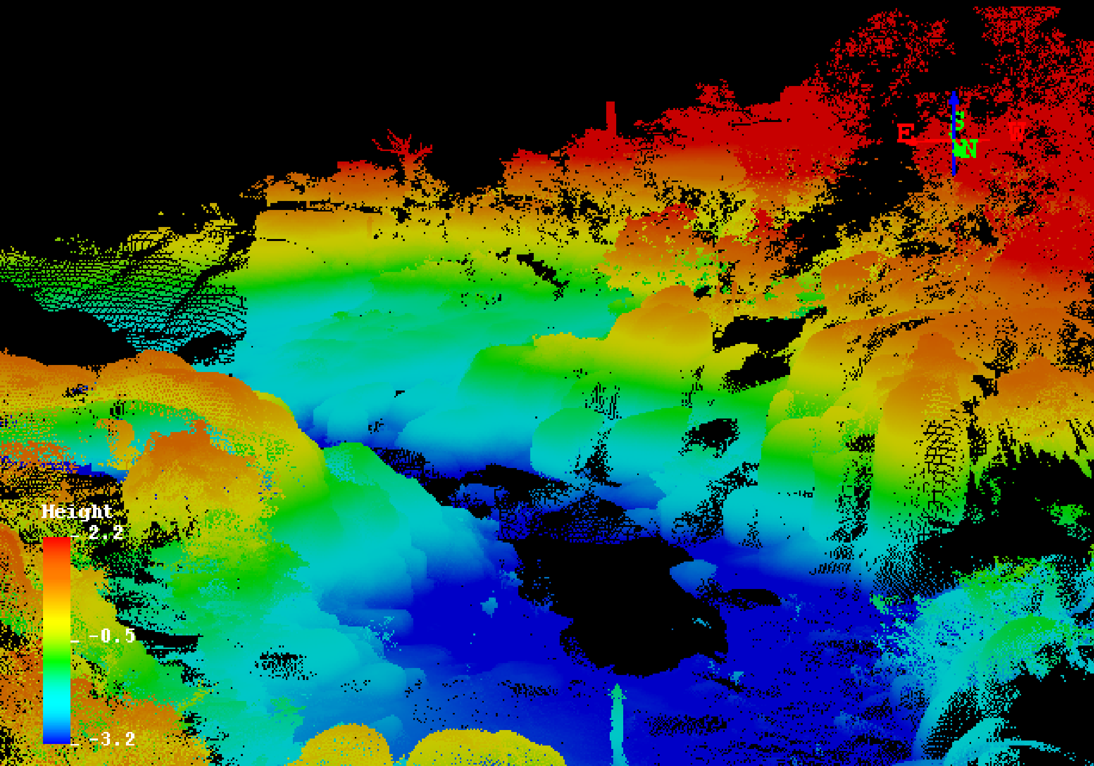
Applies in particular to statistical self similarity

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

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

B. B. Mandelbrot


USGS 10 m/pix NED
B4 lidar 0.5 m/pix
B4
Drainage > 100 sq. m
N
0
0.25
0.5
1 Kilometers
B4
B4 lidar 0.5 m/pix
USGS 10 m/pix NED



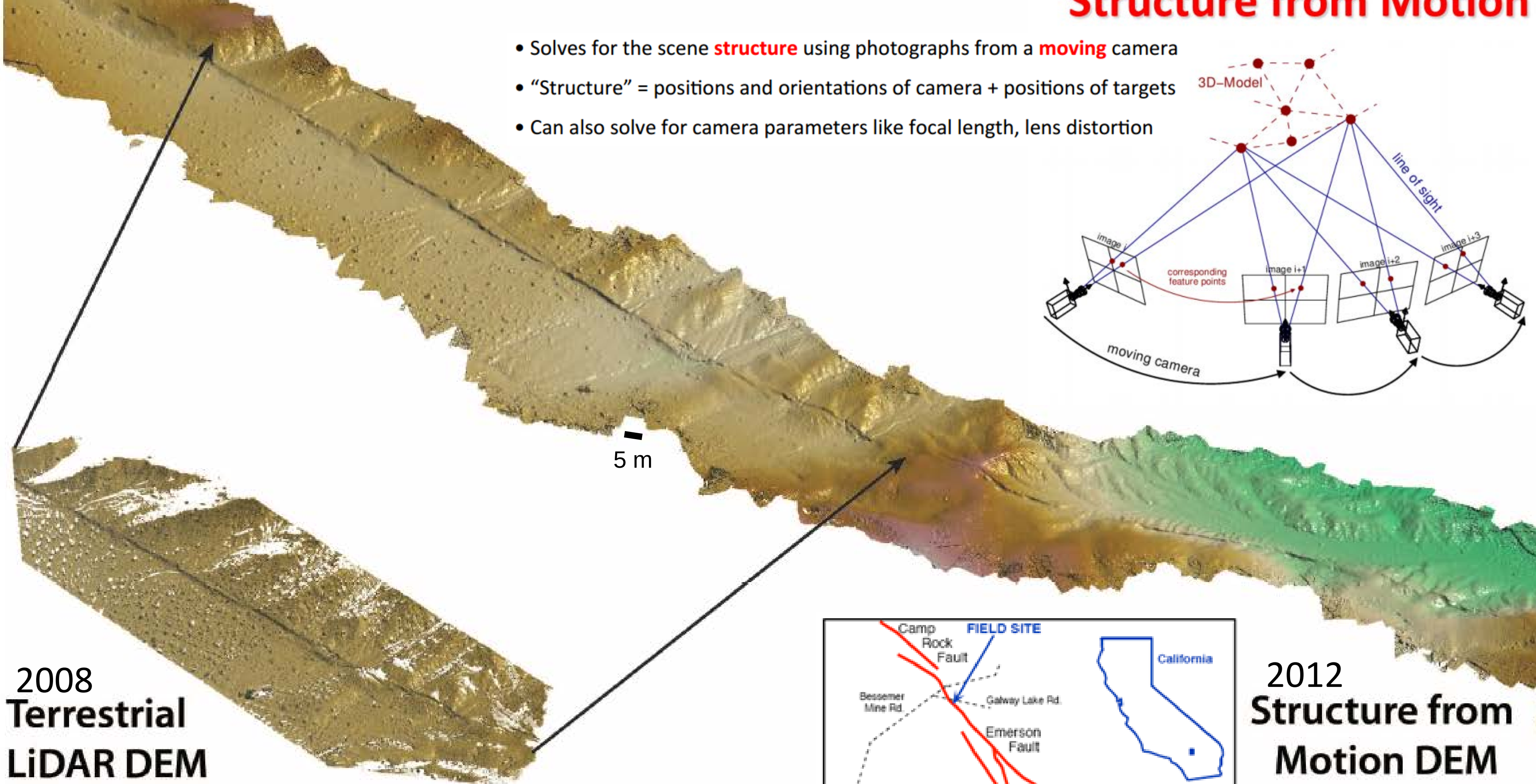
Granite Dells AZ point cloud (Haddad, et al. 2012)

UNAVCO Terrestrial Laser Scanner

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

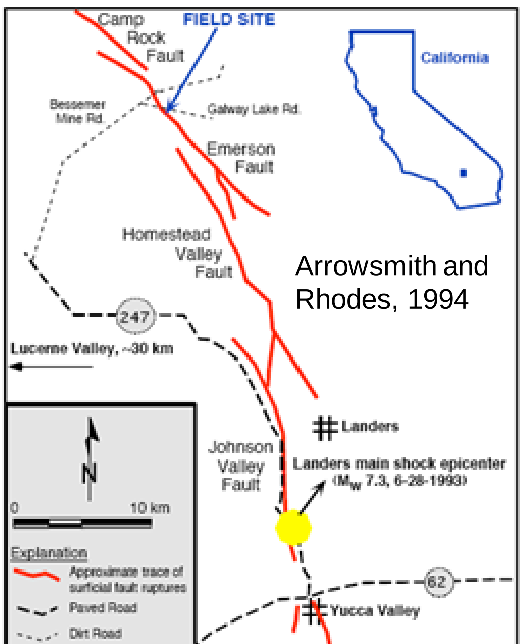
Structure from Motion

- 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

Main Application types

- **Feature mapping at fine scale**
- Landscape reconstruction (offsets)
- Surface process interactions with tectonic processes
- Differencing of repeat surveys

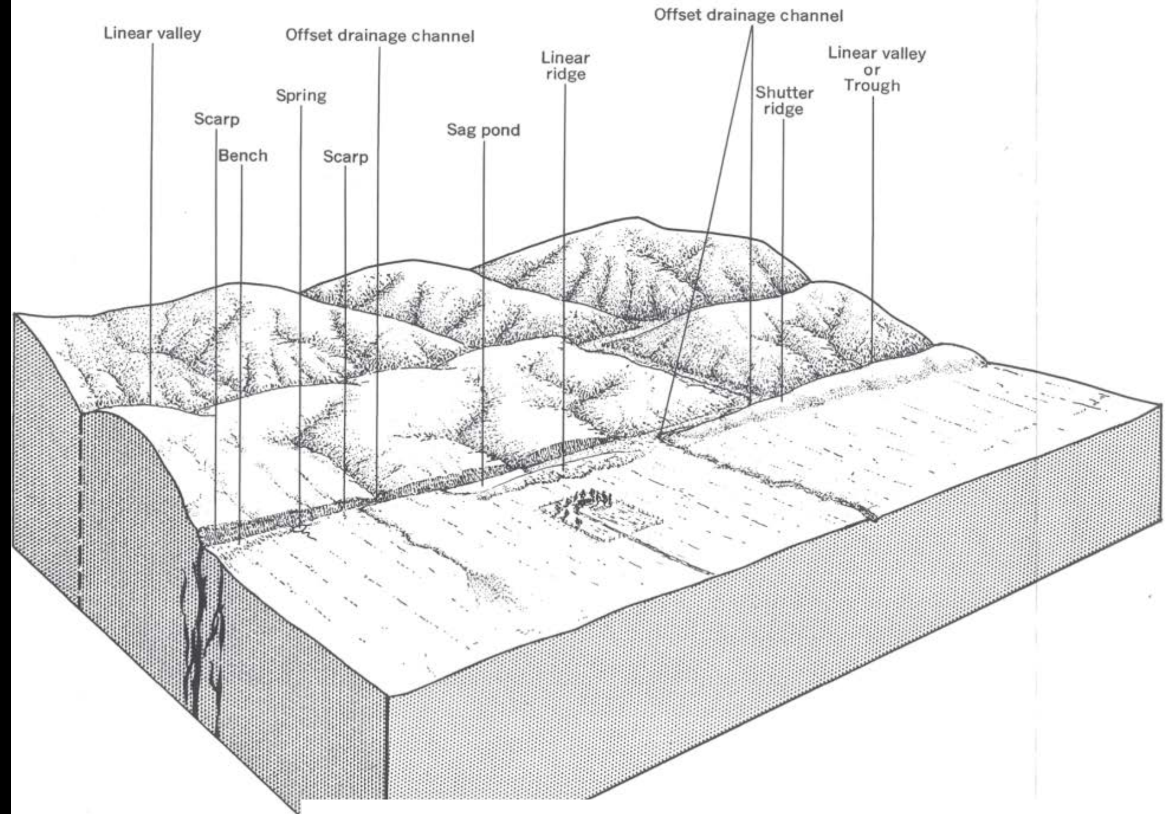
Northern San Andreas Fault, California

Northern San Andreas Fault, California

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

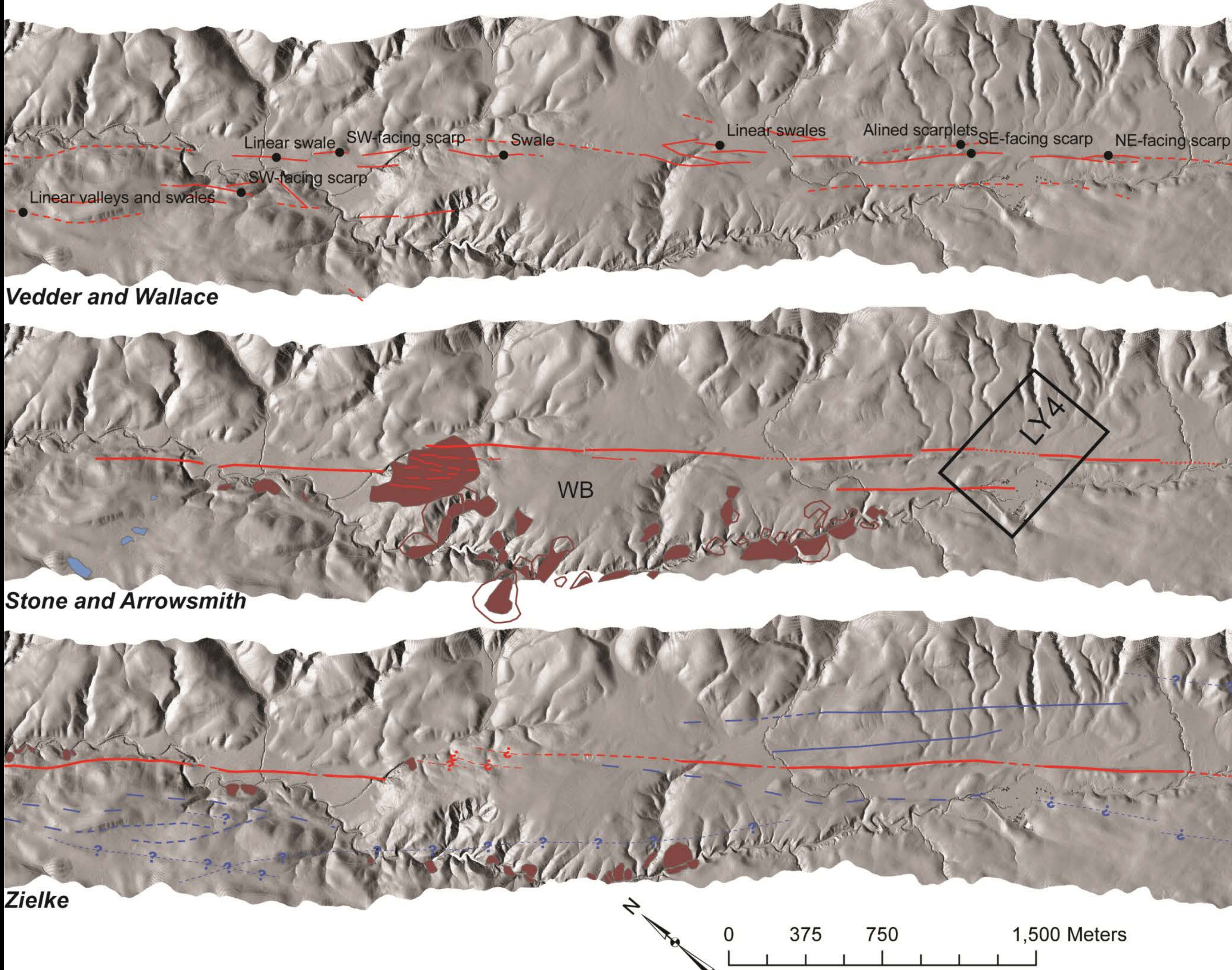
Stone and Arrowsmith

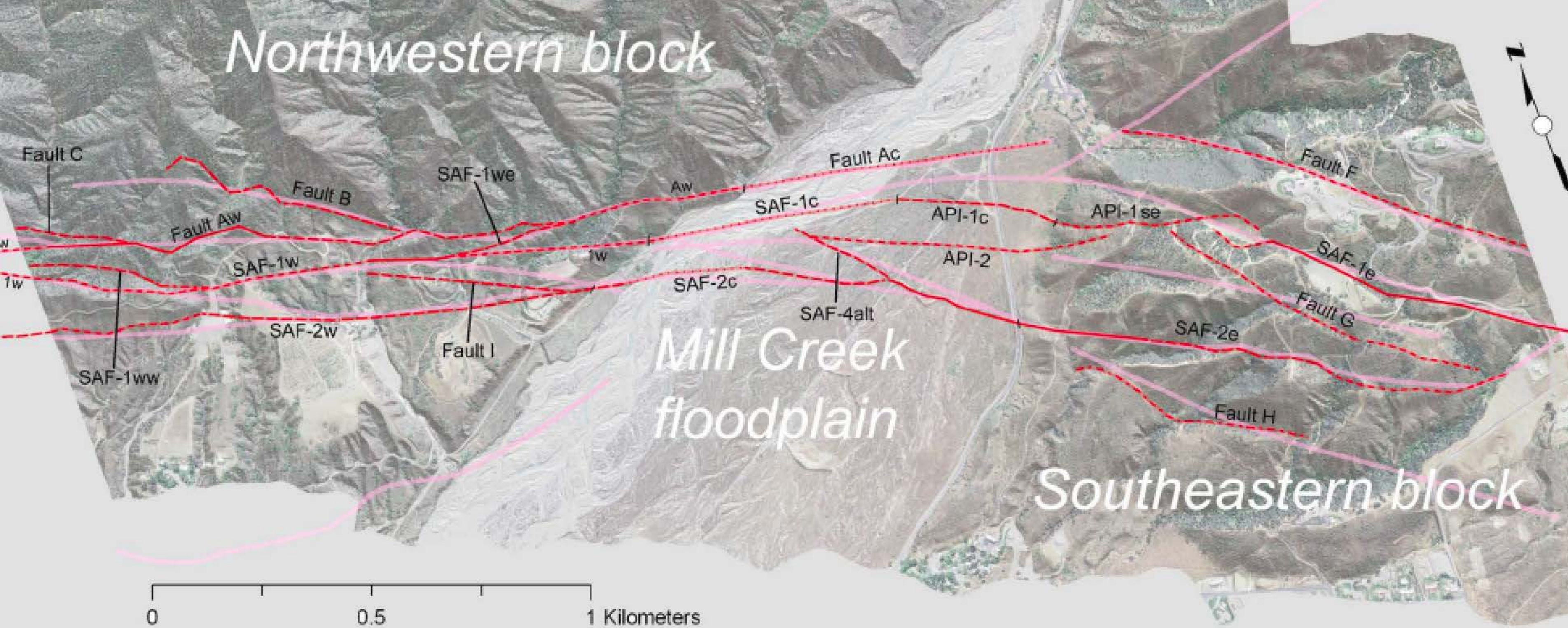
- Fault trace
- Fault trace, concealed
- Fault trace, inferred
- Lineament
- Landslide deposit
- Landslide scarp
- Sag

Zielke, this study

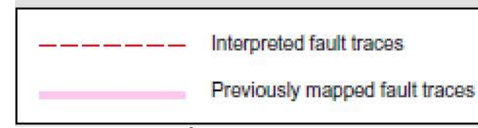
Fault traces: red for main trace, blue for secondary traces

- 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



Lidar higher resolution and greatest accuracy:
- discern multiple close traces
- well suited to combine with imagery
- basemap for location of features

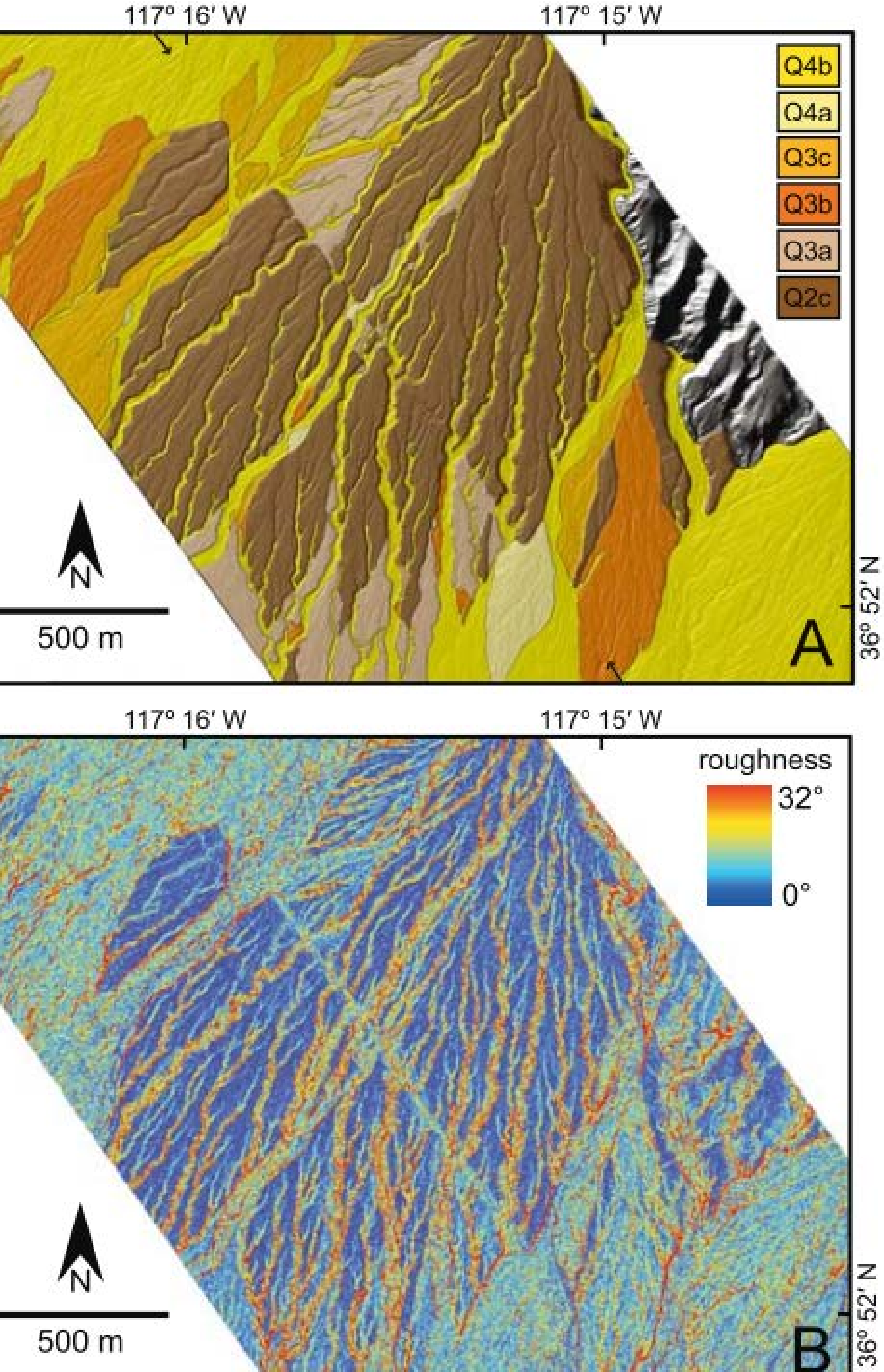


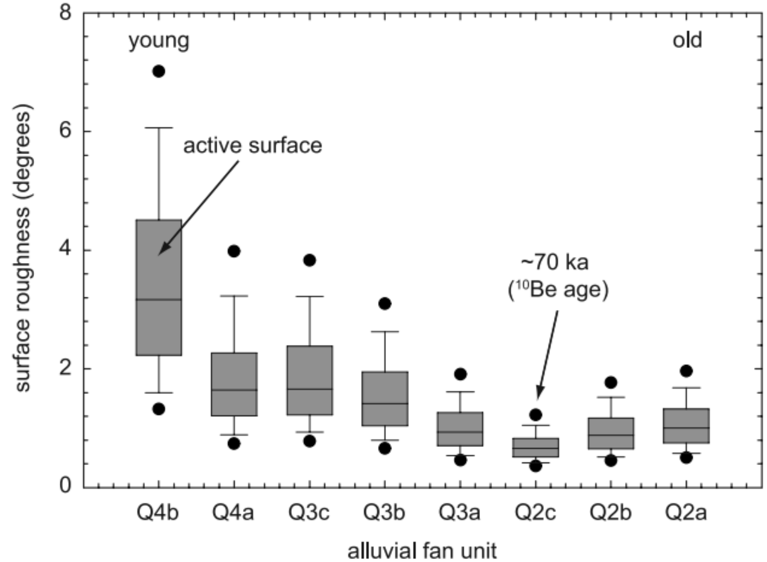
Treiman, Perez, & Bryant, 2010, USGS Award No. 08HQGR0096
Final Tech. Repor

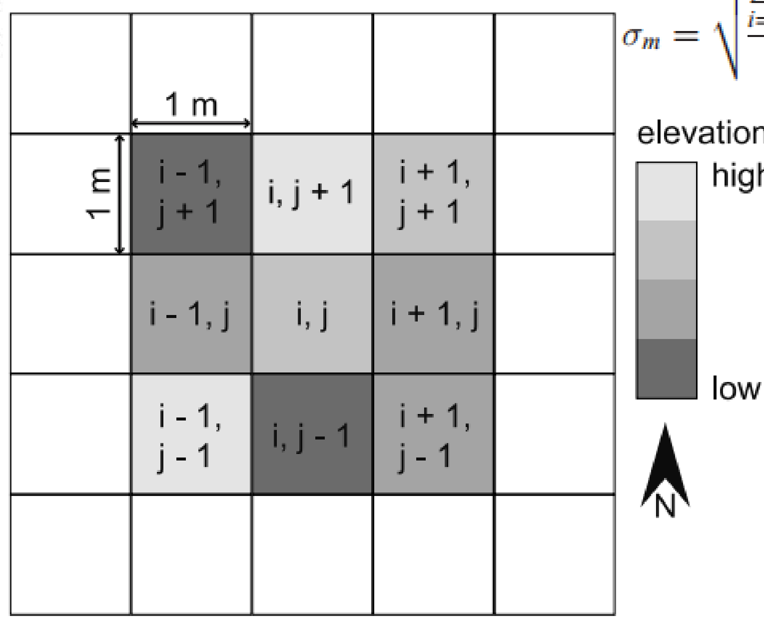
NW Block

Fault Trace	TERRAIN / FIELD Conditions				Imagery Type									BEST IMAGERY
	Slope	Vegetation	Geology	Remarks	AP	LiDAR	NAIP	ISTAR	STEREO	Draped NAIP	Draped ISTAR	Fused NAIP T	Fused NAIP F	
SAF-1w	moderate to high	moderate to dense	gg/Qof,Qyf	separates geologic units	5	4				5	5			LiDAR
SAF-1ww	moderate	moderate	gg/Qof,Qyf	faceted slopes	1	4			3	3			4	AP
SAF-1we	moderate	light to moderate	gg	alignment of features	1	1	4		1	3			5	AP or Stereo, LiDAR
SAF-2w	moderate to low	light to moderate	Qof,Qyf		4	4			4	4	4	4	4	all together

Going beyond pretty pictures: the hillshades are very nice, but…





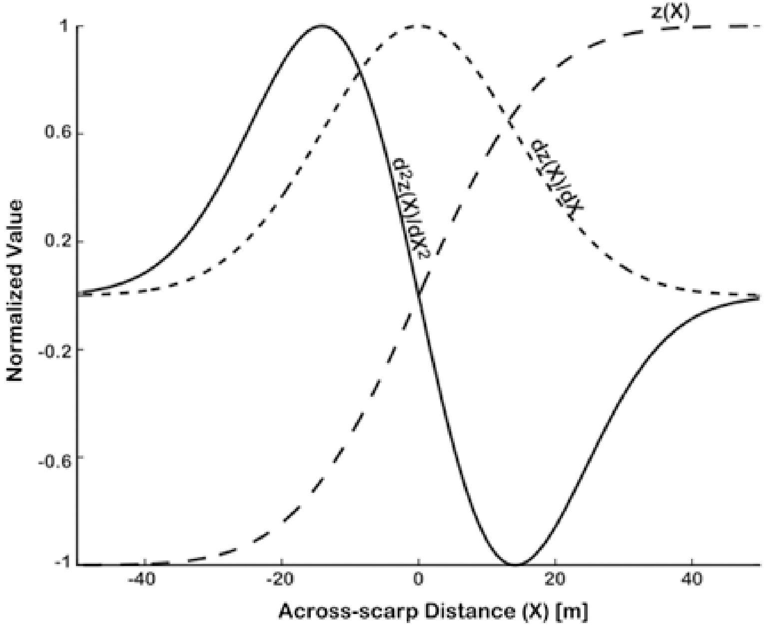


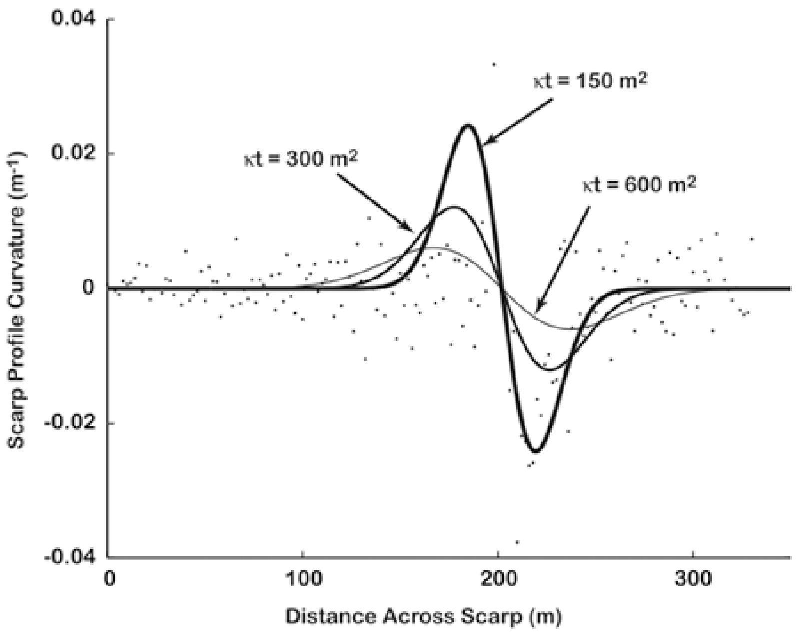
$$\sigma_m = \sqrt{\frac{\sum_{i=1}^{n} (m_i - \overline{m})^2}{n}},$$

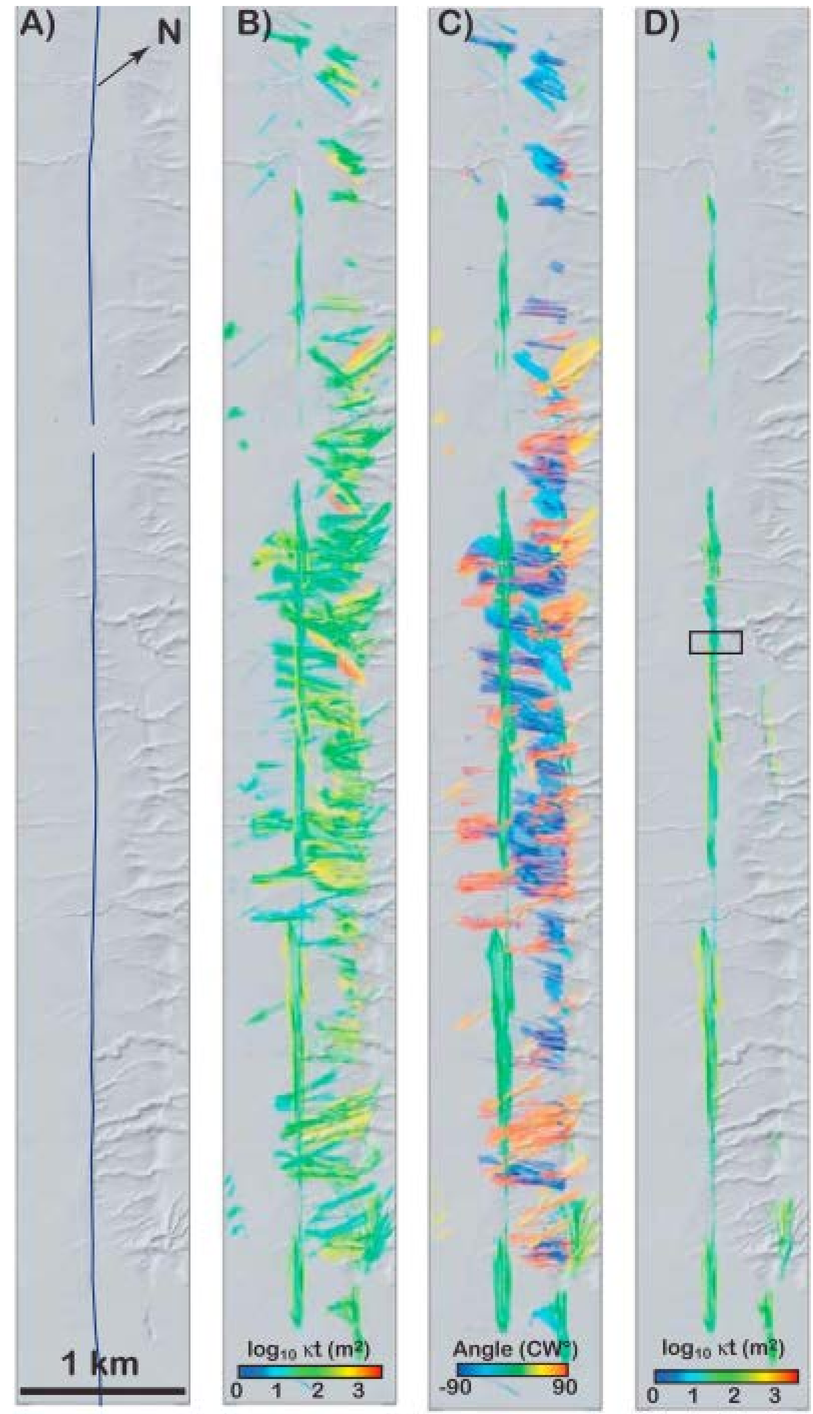
Characterizing arid region alluvial fan surface roughness with airborne laser swath mapping digital topographic data

Kurt L. Frankel[1] and James F. Dolan[1]

JGR, 2007







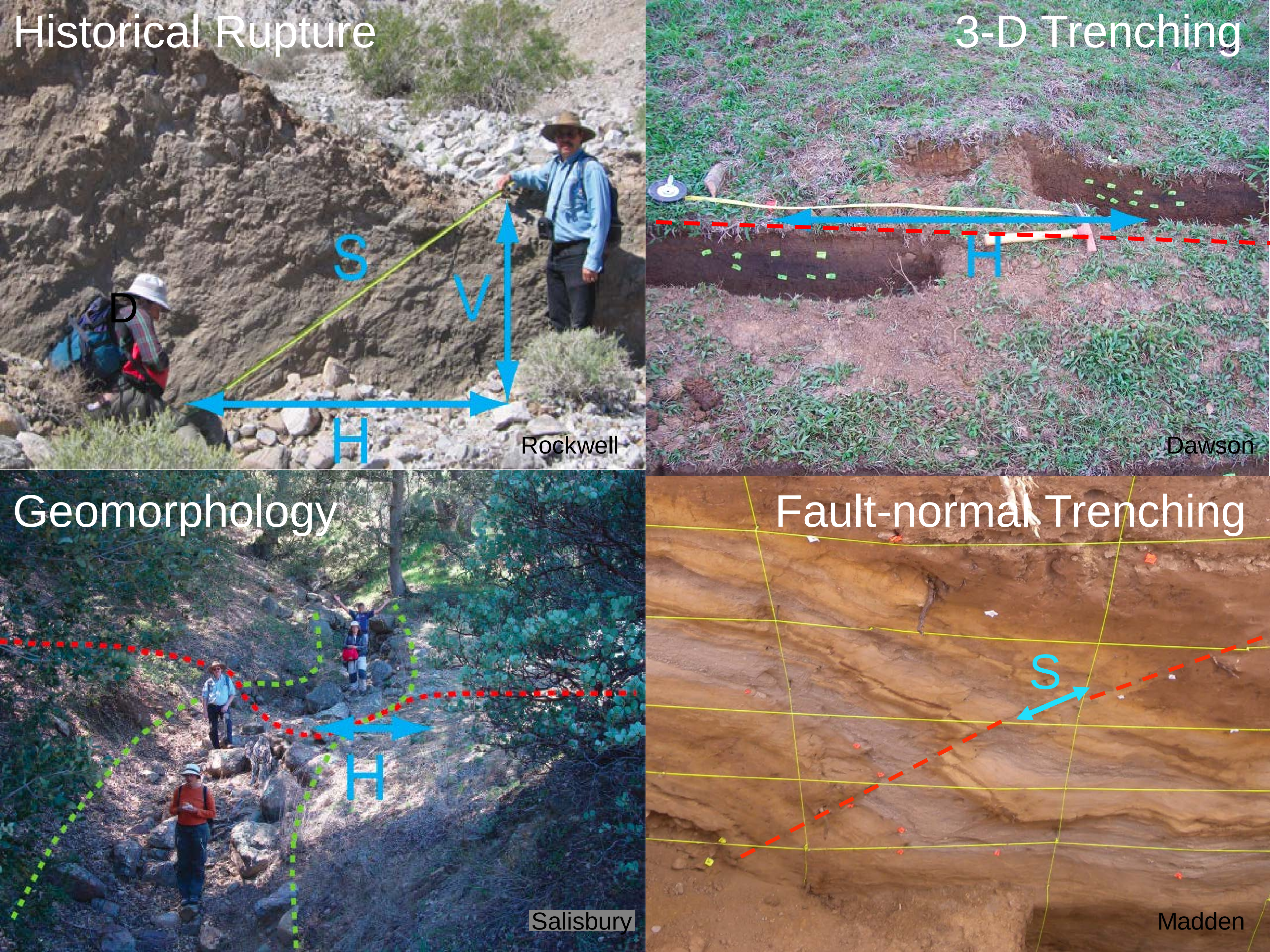
Morphologic dating of fault scarps using airborne laser swath mapping (ALSM) data

GRL, 2010

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

Main Application types

- Feature mapping at fine scale
- **Landscape reconstruction (offsets)**
- Surface process interactions with tectonic processes
- Differencing of repeat surveys


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

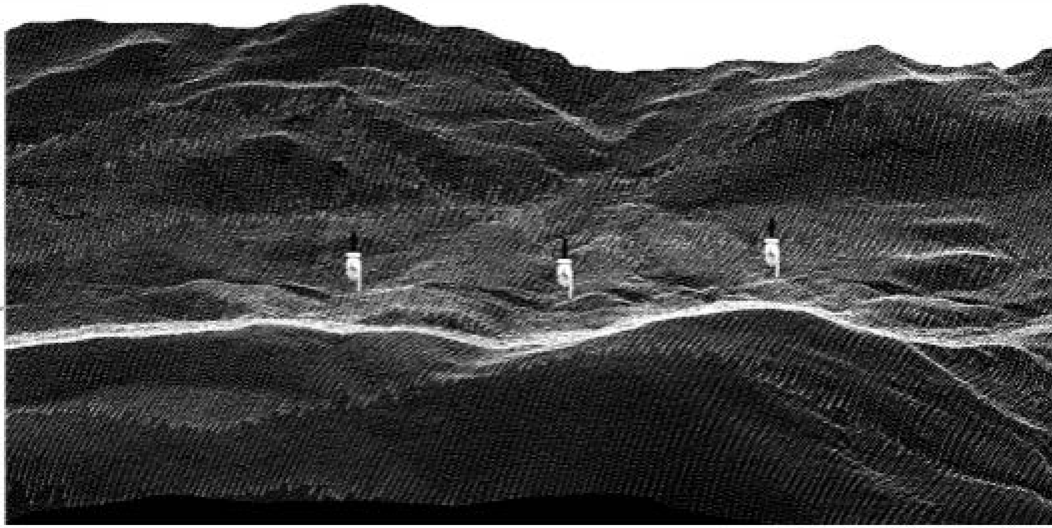


Figure 2. Oblique view of Hector Mine earthquake surface rupture that experienced 3.5–4.5 m of right-lateral displacement. The rupture trace is pointed out by finger icons; the light and dark bands below and above the surface rupture are subparallel, topographic escarpments. Several offset ridges are now juxtaposed with gullies, forming 'shutter' ridges. Raw laser hits are used to illuminate the ground surface in this point-cloud image. From tens to hundreds of hits per square meter were collected along the primary surface ruptures.

Bulletin of the Seismological Society of America, Vol. 92, No. 4, pp. 1570–1576, May 2002

High-Resolution Topography along Surface Rupture of the 16 October 1999 Hector Mine, California, Earthquake (M_w 7.1) from Airborne Laser Swath Mapping

by K. W. Hudnut, A. Borsa, C. Glennie, and J.-B. Minster

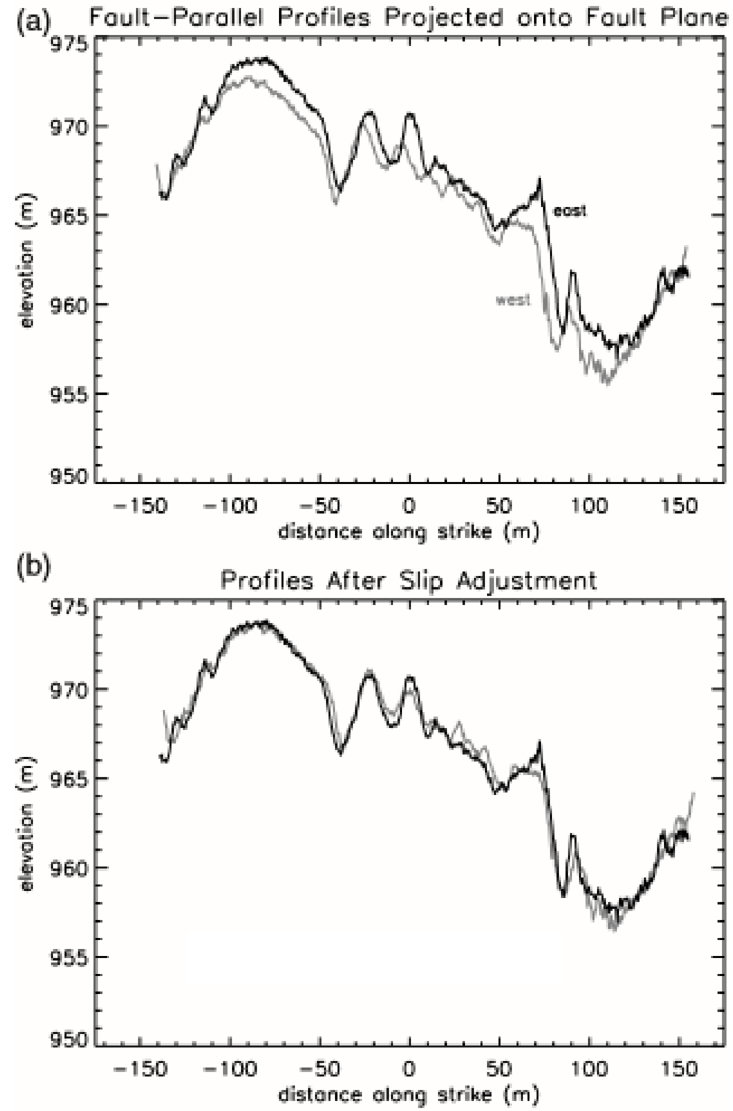
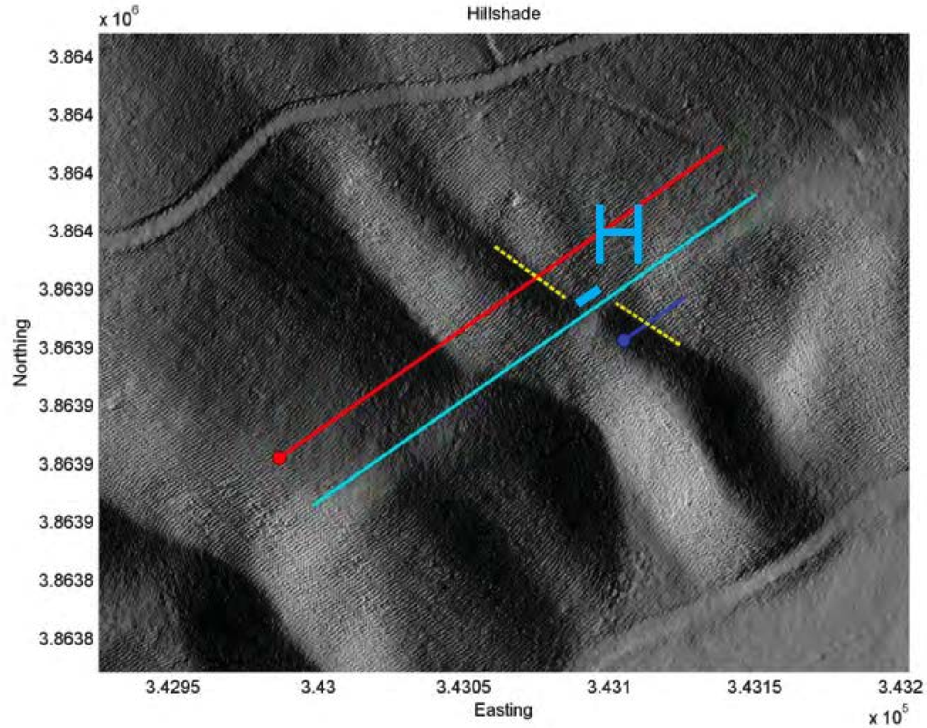
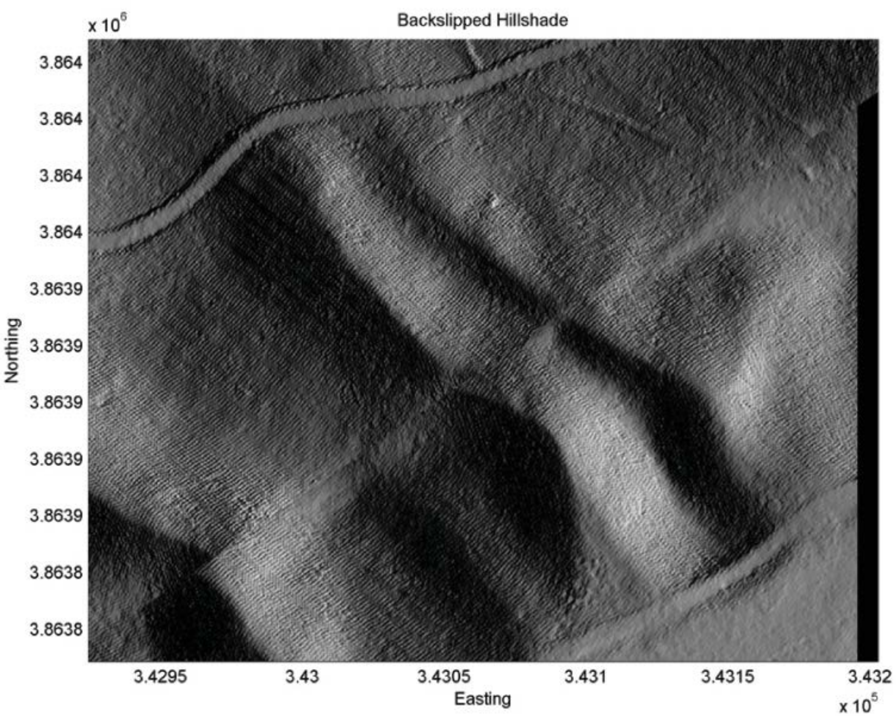
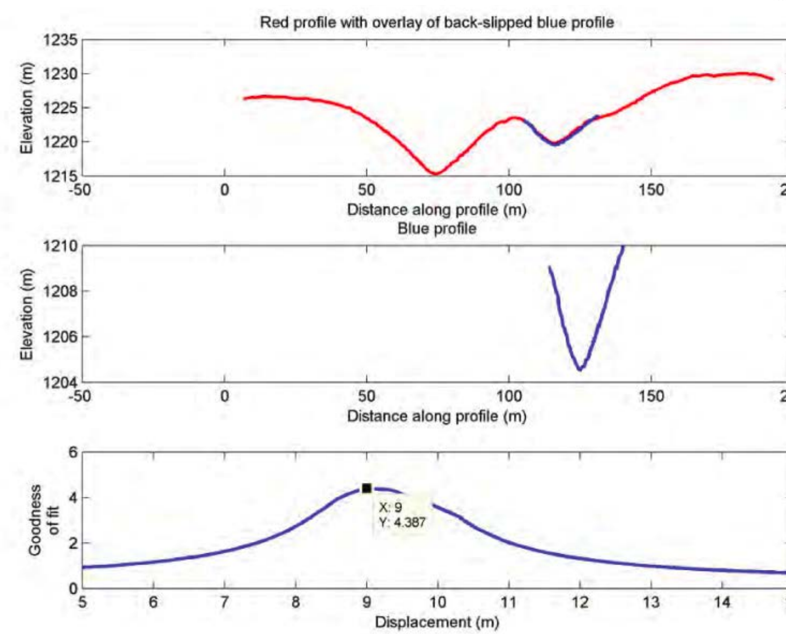


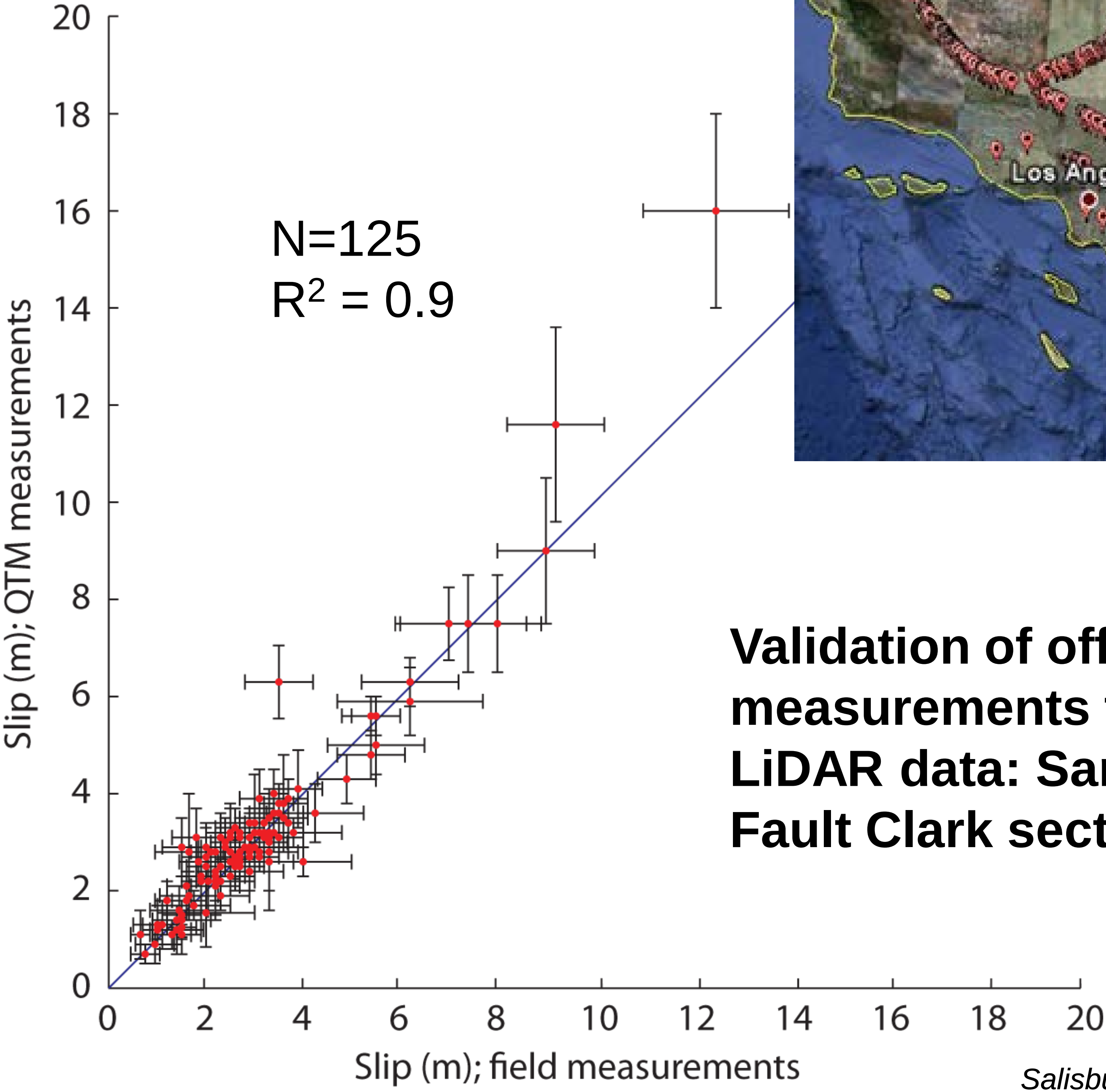
Figure 6. (a) Cross sections through the raw laser data on either side of the surface rupture, along the east and west profiles shown in Figure 4, are shown projected onto the fault plane (a ground-slope correction has already been removed). (b) Comparison of the topographic profiles on either side of the fault, after shifting the profiles shown in Figure 6a to remove our best estimate of the lateral and vertical offset along this 300-m section.

LiDAR Measurements



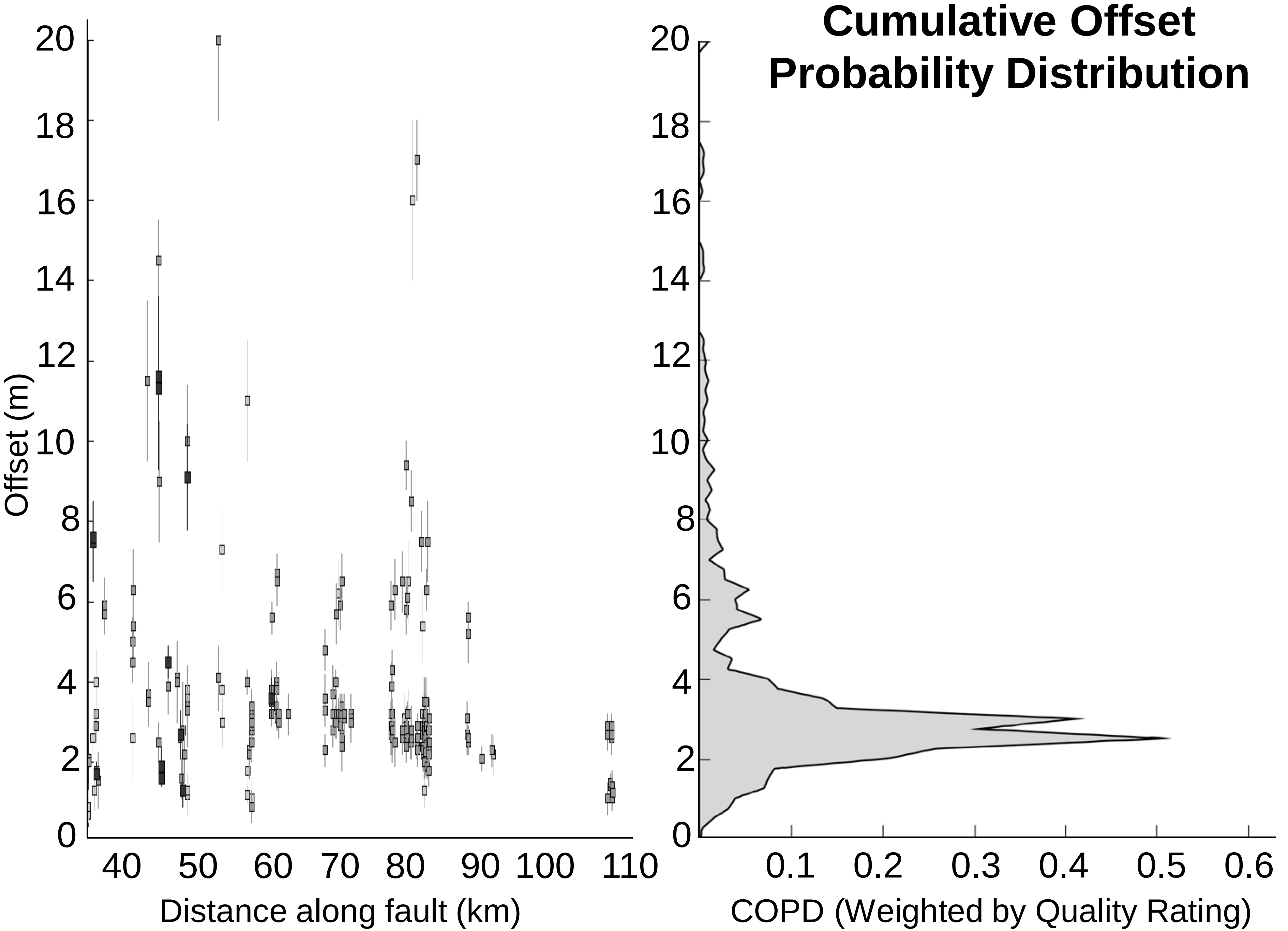




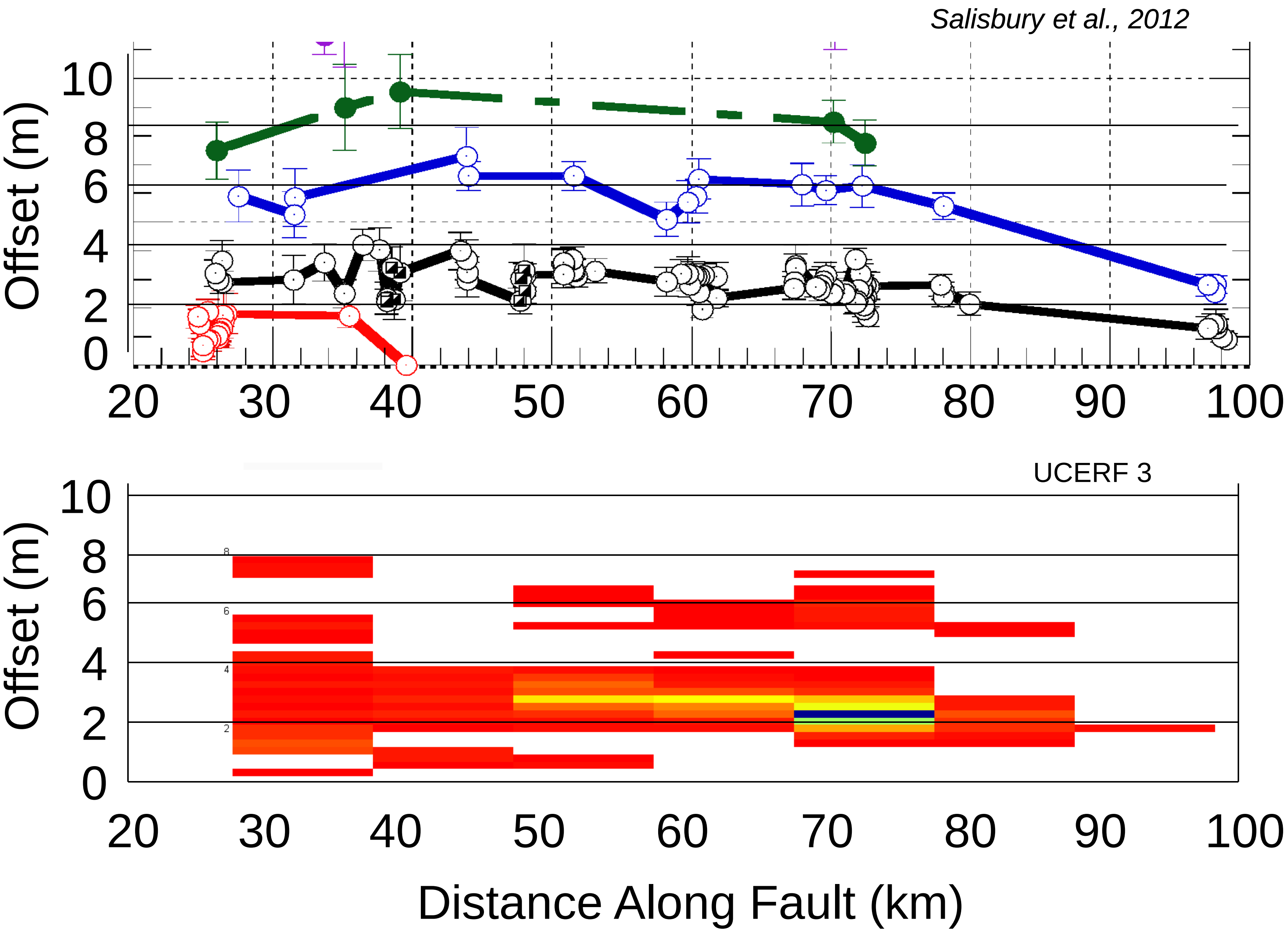


Validation of offset measurements from field and LiDAR data: San Jacinto Fault Clark section

Salisbury et al., 2012



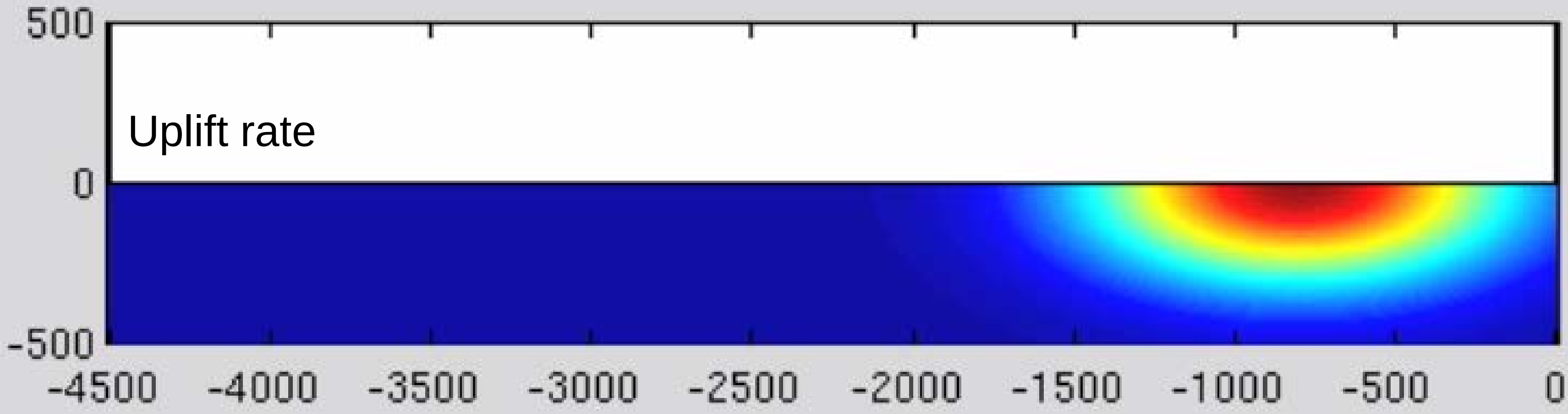
Cumulative Offset Probability Distribution
Offset (m)
20
18
16
14
12
10
8
6
4
2
0
40
50
60
70
80
90
100
110
Distance along fault (km)
0.1
0.2
0.3
0.4
0.5
0.6
COPD (Weighted by Quality Rating)


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

Main Application types

- Feature mapping at fine scale
- Landscape reconstruction (offsets)
- **Surface process interactions with tectonic processes**
- Differencing of repeat surveys

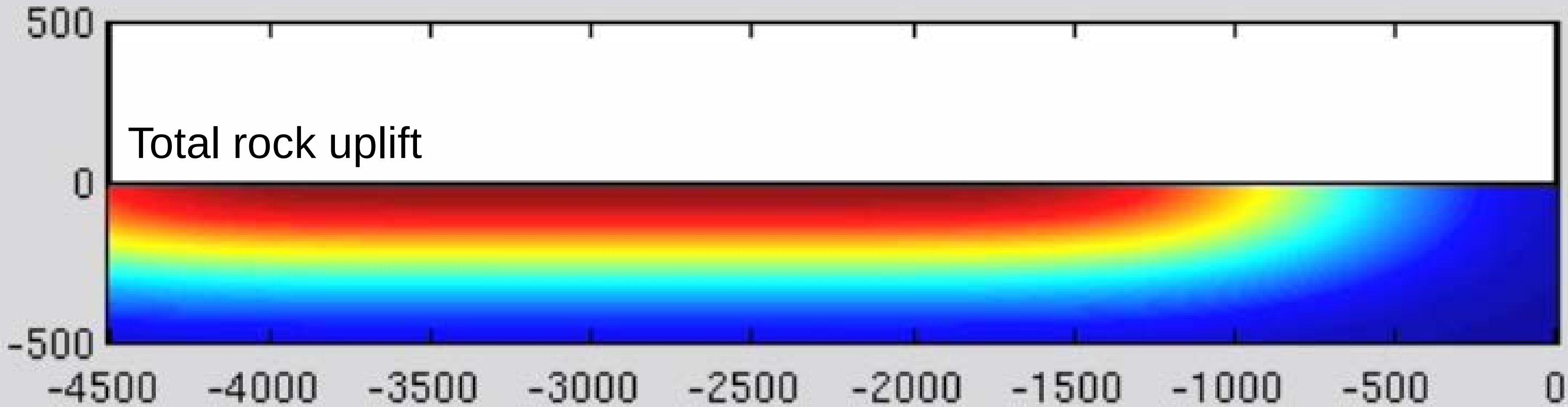
Understanding geomorphic response to uplift



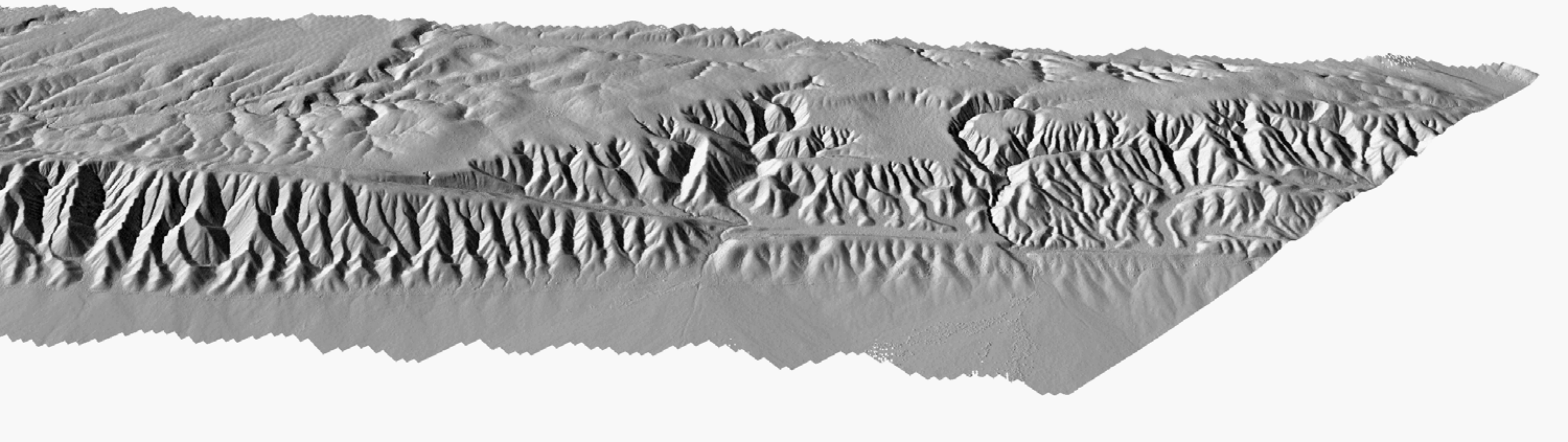
Material moves along fault though relatively stationary uplift zone:

How does landscape respond?

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

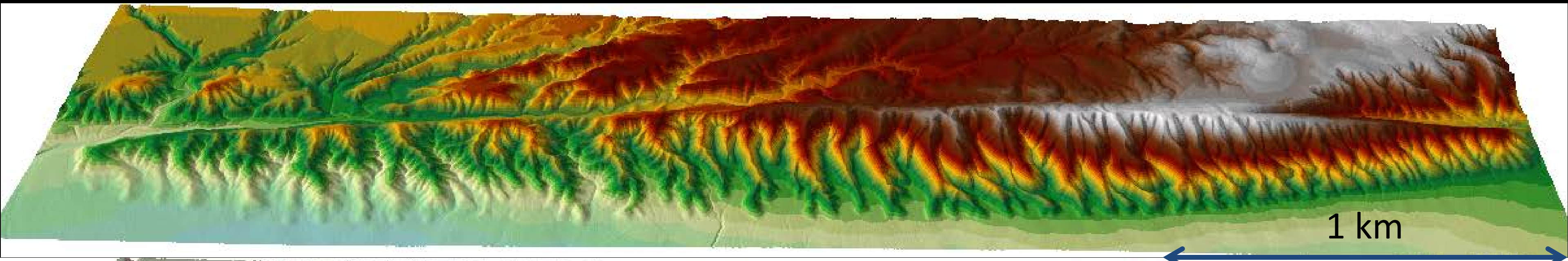


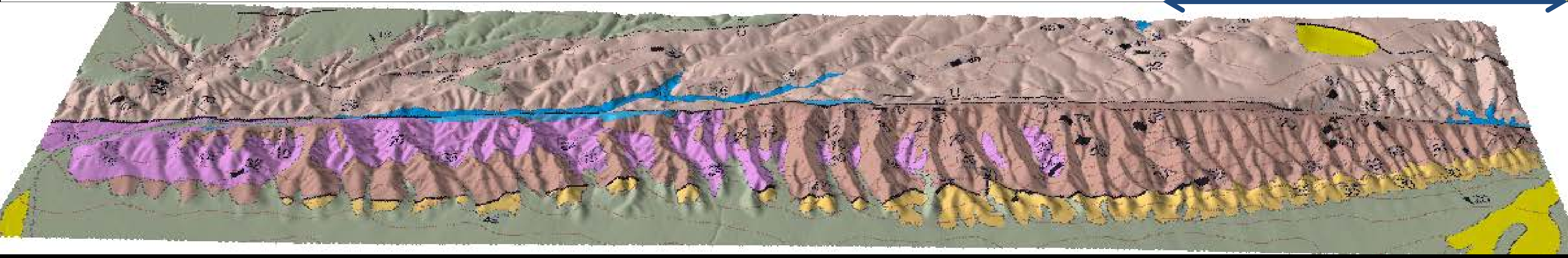
-G. E. Hilley

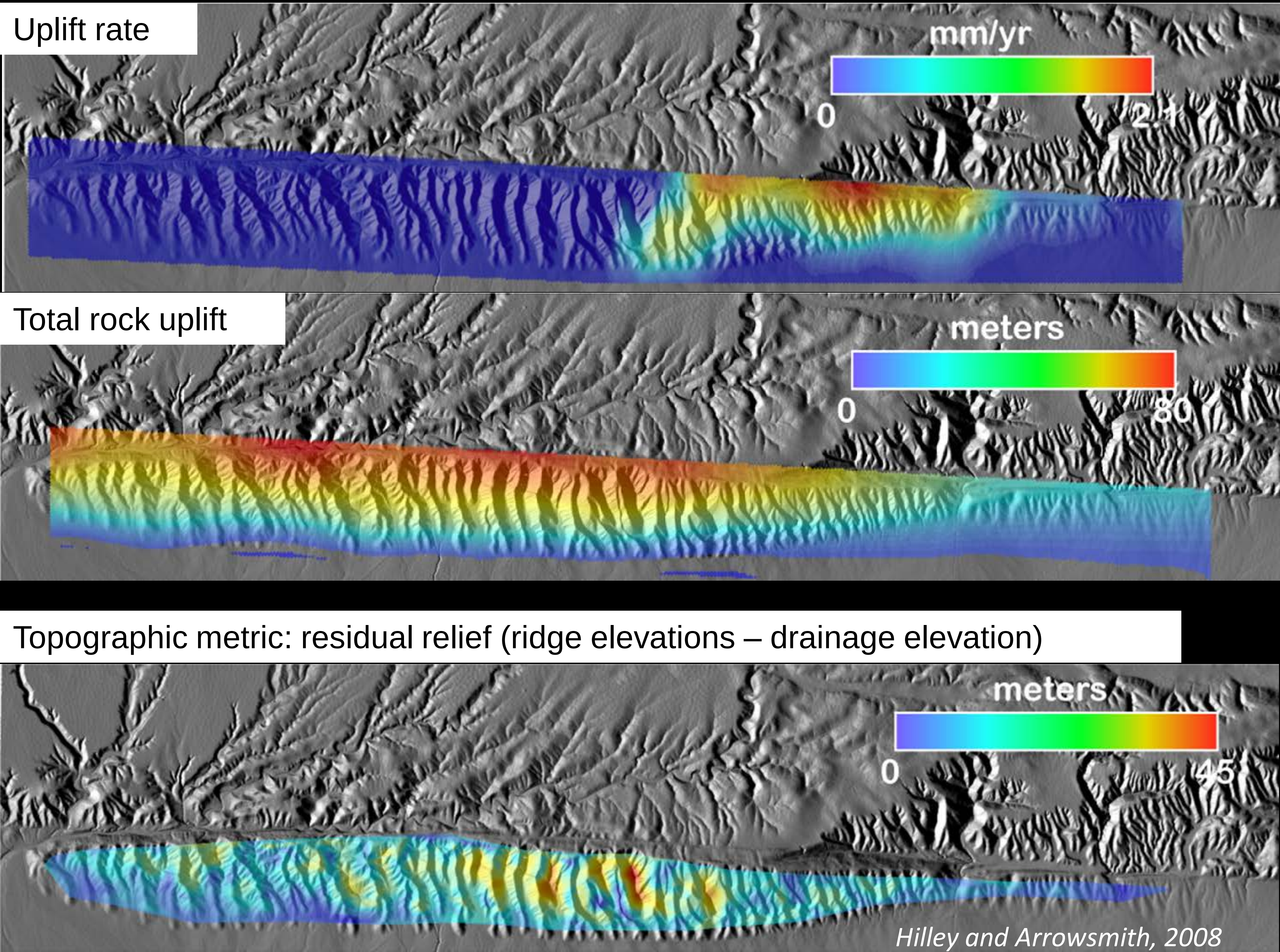


Dragon’s Back Pressure Ridge, Carrizo Plain California

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







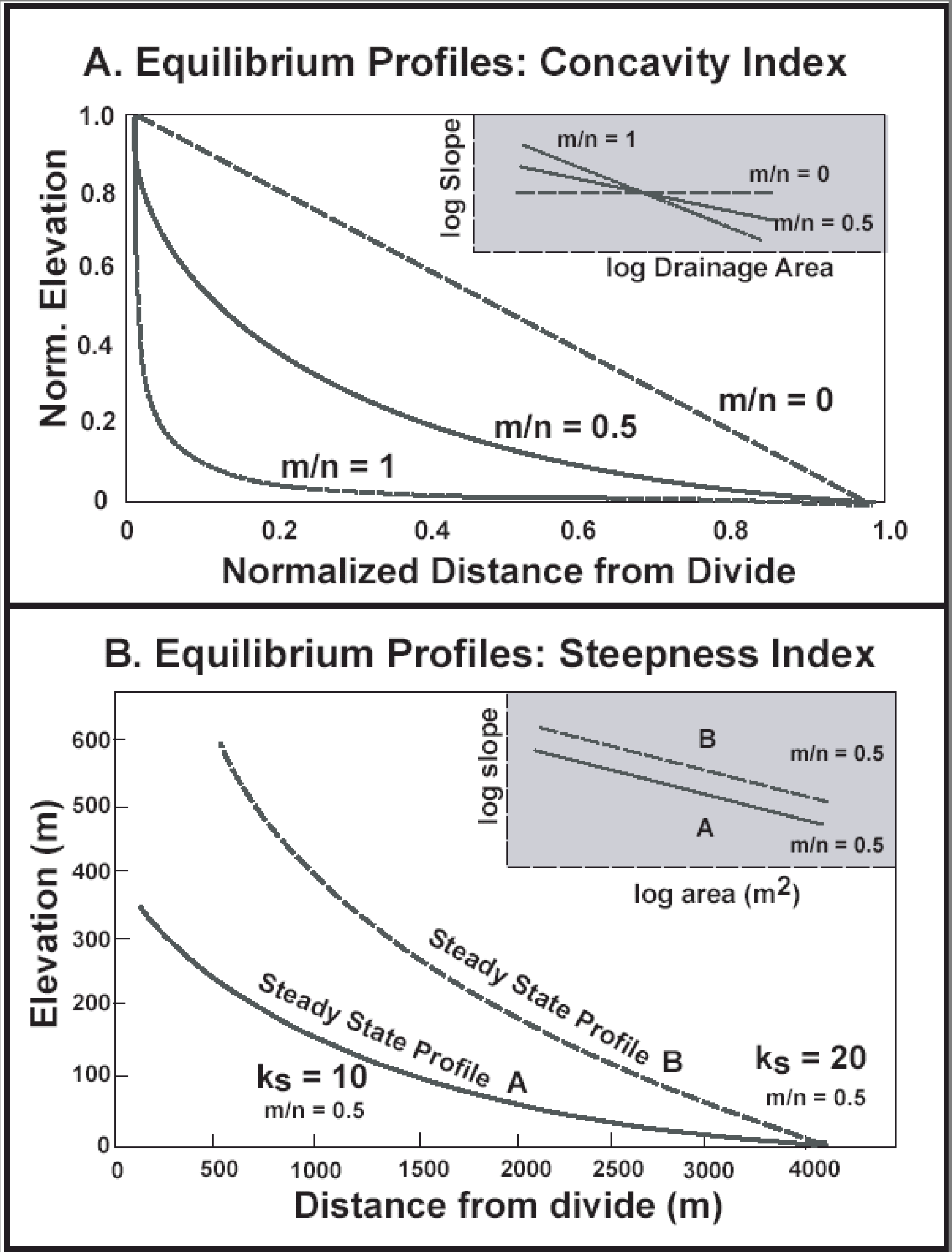
Uplift rate
mm/yr
0
2.1
Total rock uplift
meters
0
80
Topographic metric: residual relief (ridge elevations – drainage elevation)
meters
0
45
Hilley and Arrowsmith, 2008

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

U = Rock Uplift Rate

Concavity (θ) invariant with U

Steepness (Ks) varies with U

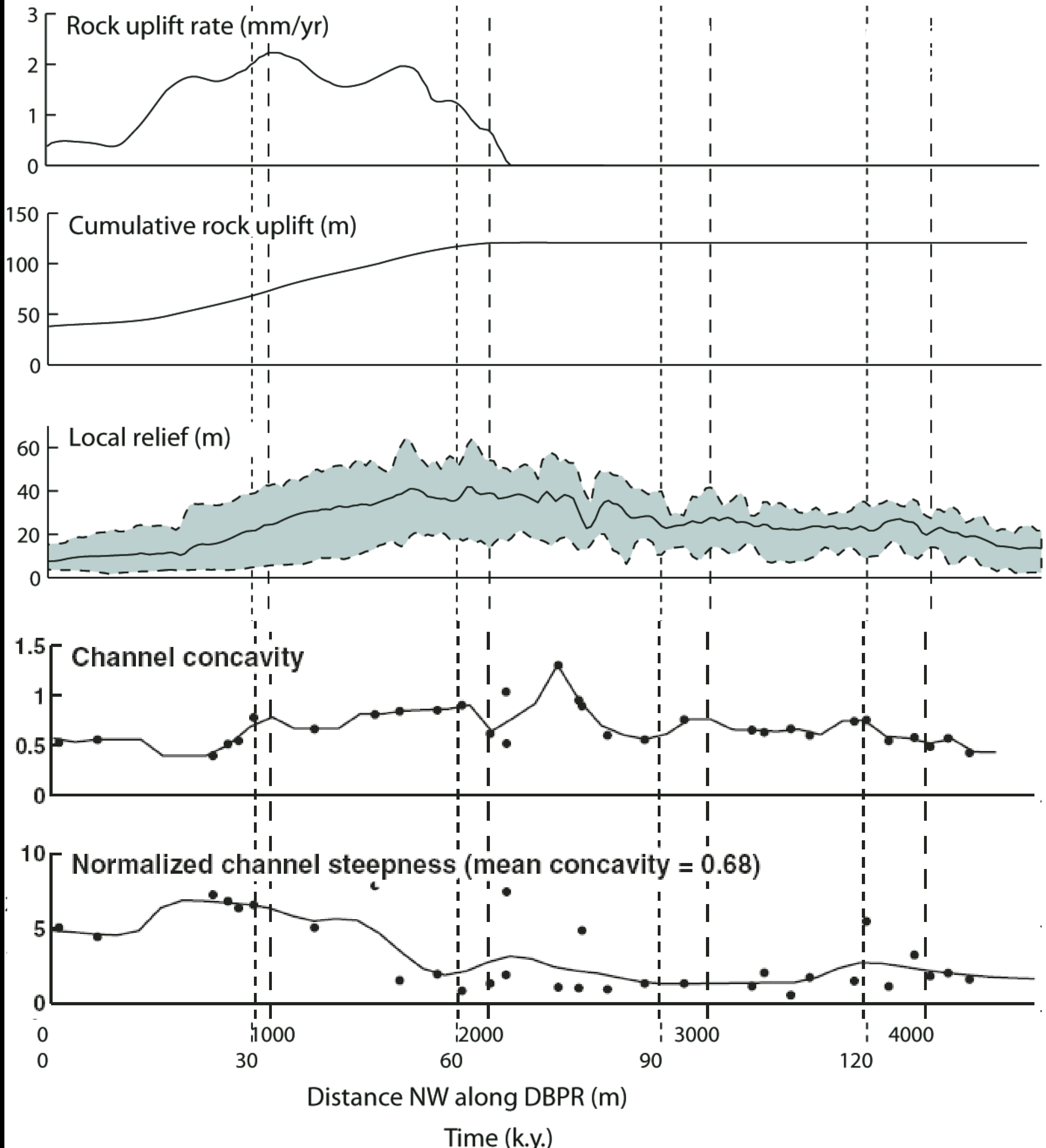


$\theta = m/n$

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

k_s

--K. X Whipple



Hilley and Arrowsmith, 2008

Main Application types

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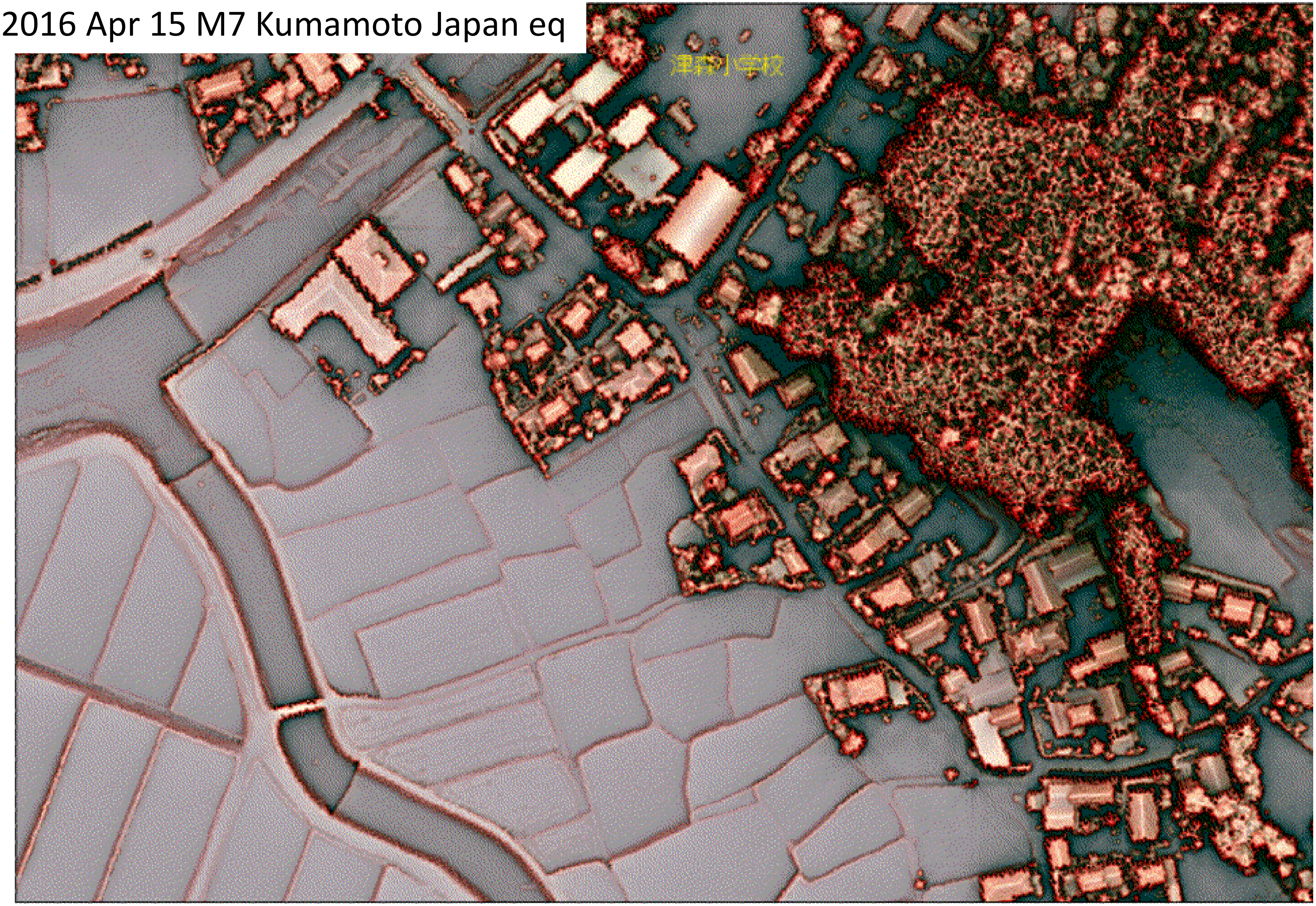
- Landscape reconstruction (offsets)
- Surface process interactions with tectonic processes
- **Differencing of repeat surveys**

2016 Apr 15 M7 Kumamoto Japan eq

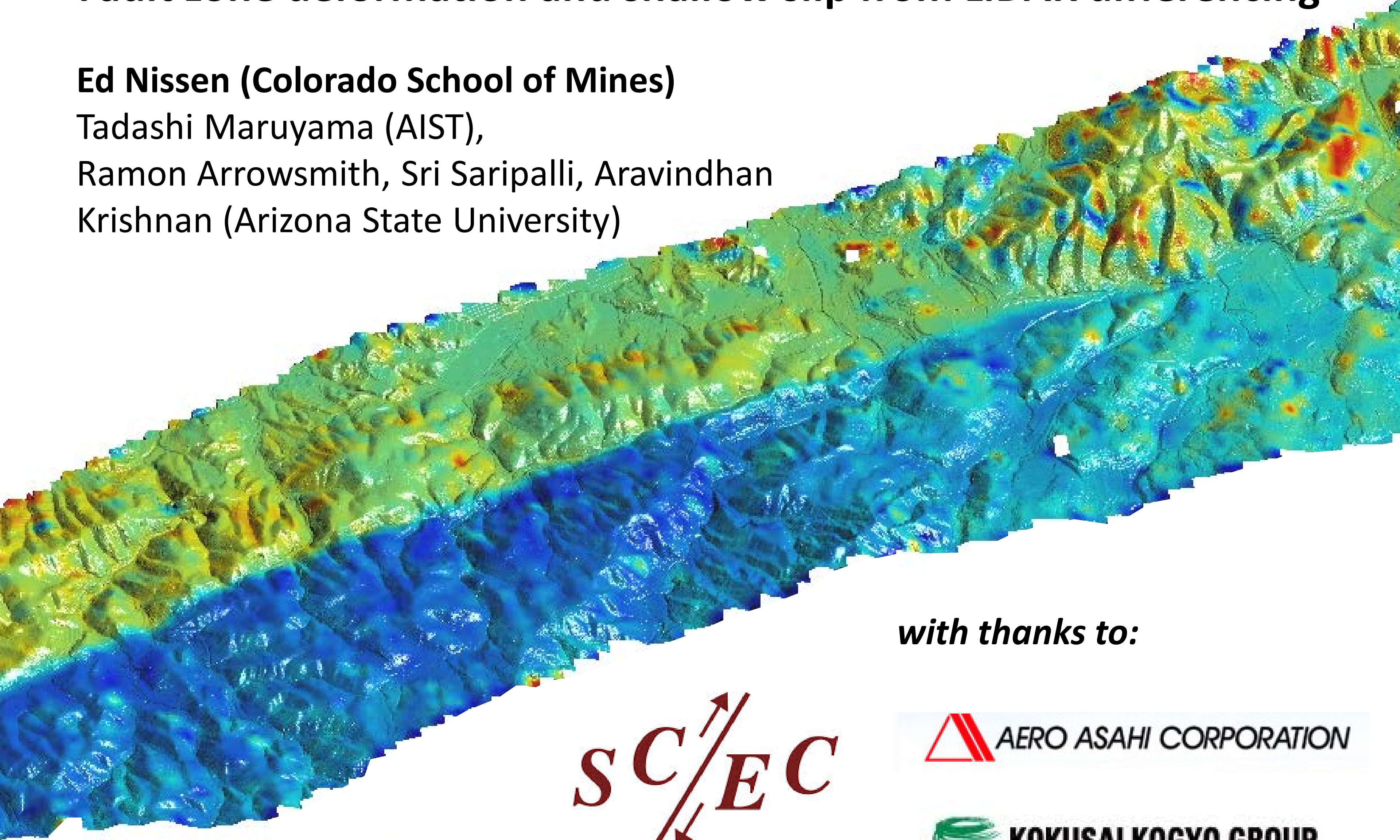


4/15計測　DSMデータによる赤色立体地図
益城町　津森小学校周辺

http://www.ajiko.co.jp/saigai/kumamoto_2016_04_2/gif_a.gif

Fault zone deformation and shallow slip from LiDAR differencing

Ed Nissen (Colorado School of Mines)
Tadashi Maruyama (AIST),
Ramon Arrowsmith, Sri Saripalli, Aravindhan Krishnan (Arizona State University)



Vertical displacements in the 2011 Mw 6.6 Iwaki earthquake

with thanks to:

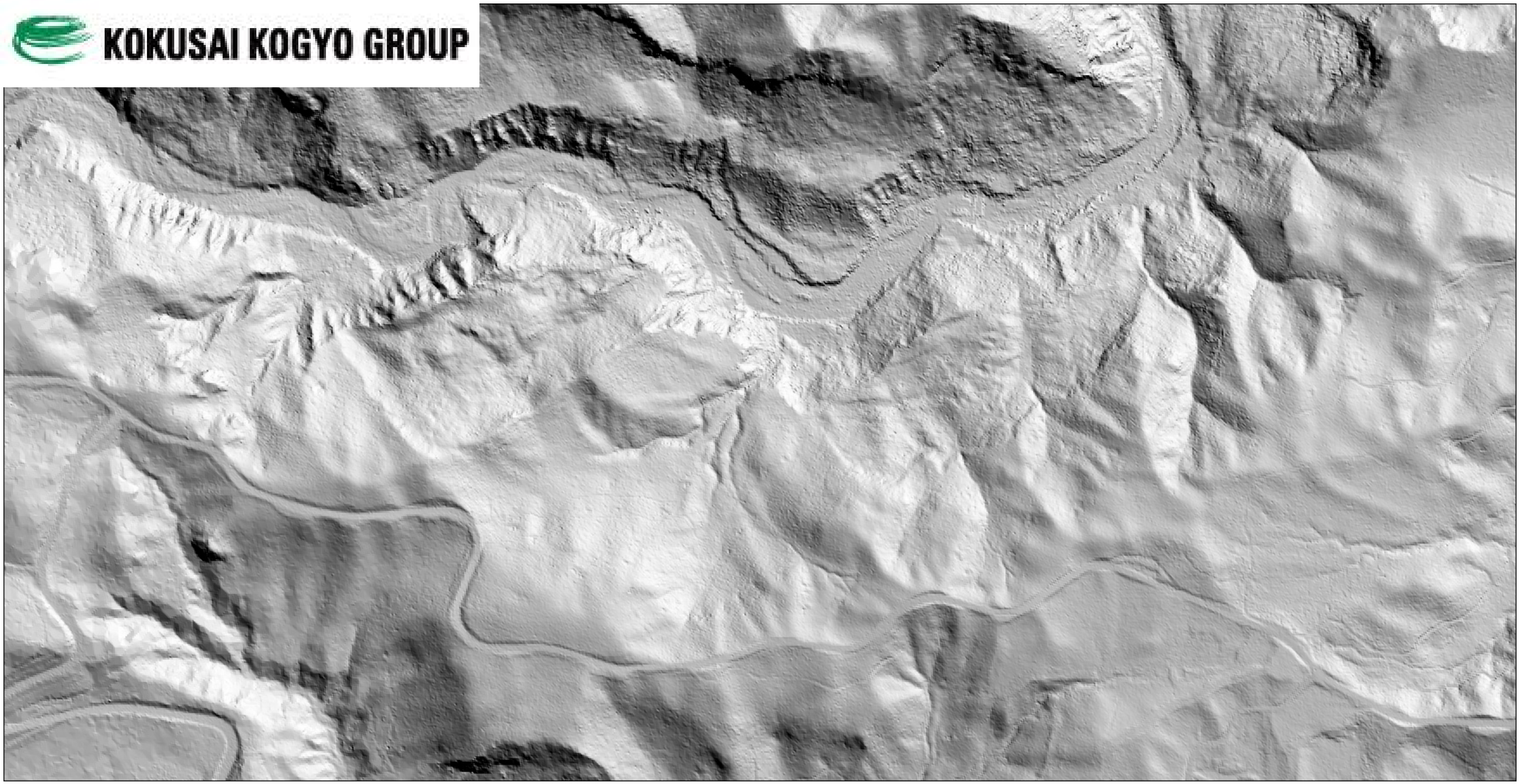
SCEC
an NSF+USGS center

AERO ASAHI CORPORATION

KOKUSAI KOGYO GROUP

-E. Nissen

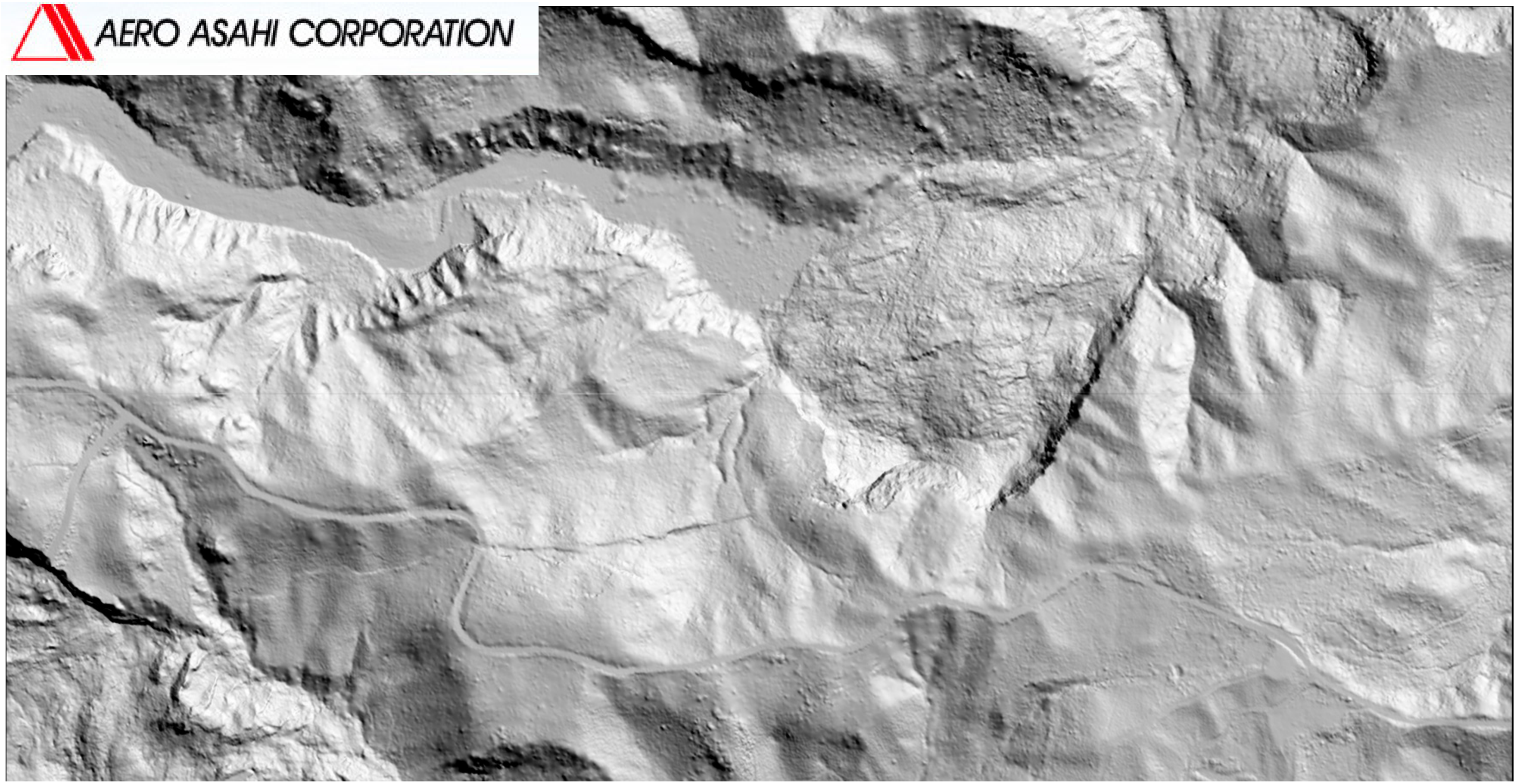
The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan



Pre-earthquake DEM (2m)

-E. Nissen

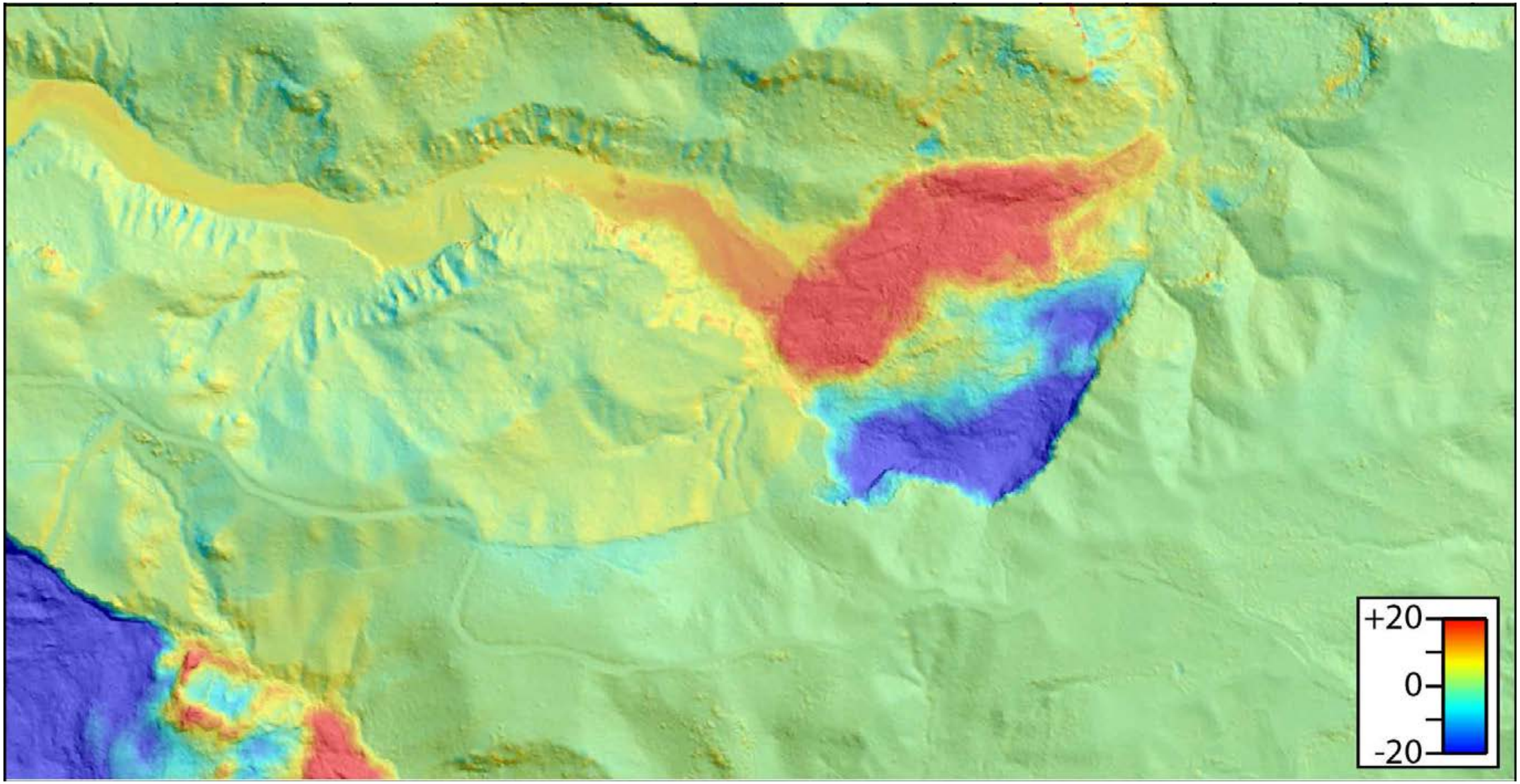
The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan



Post-earthquake DEM (1m)

-E. Nissen

14 June 2008 Iwate-Miyagi earthquake



2006-2008 vertical difference (m)

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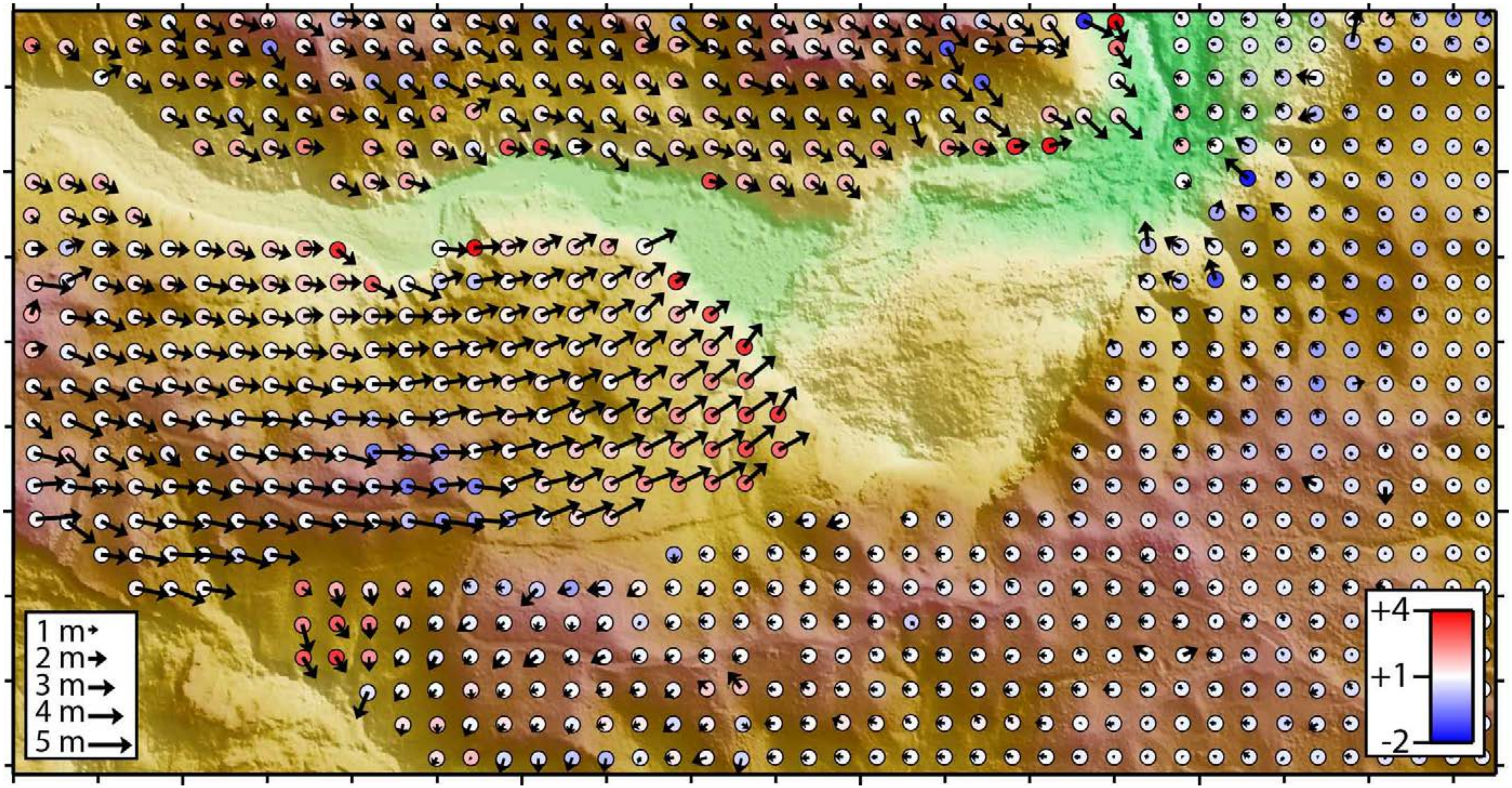
The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan



Dense 3-D displacements in an area InSAR cannot image

The displacement sense and magnitude agrees with (limited) field observations

-E. Nissen

Summary

- LiDAR provides dm to cm global accurate measure of the earth's surface
- Meter scale (high resolution topography) is critical for measuring and understanding volcanic, structural, & geomorphic processes
- Main applications in volcano- and 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 volcanic, geomorphic, and tectonic processes to geoscience education/public outreach