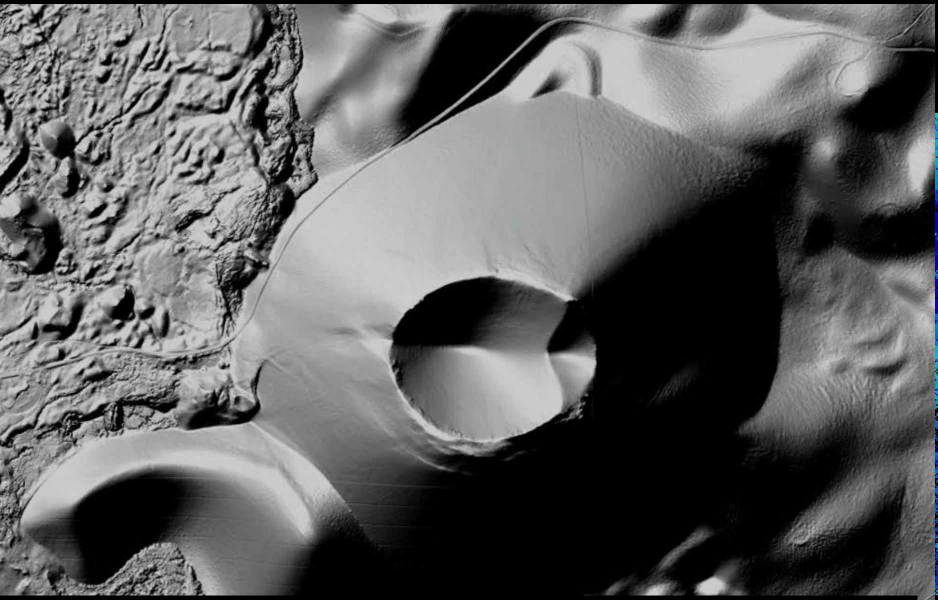
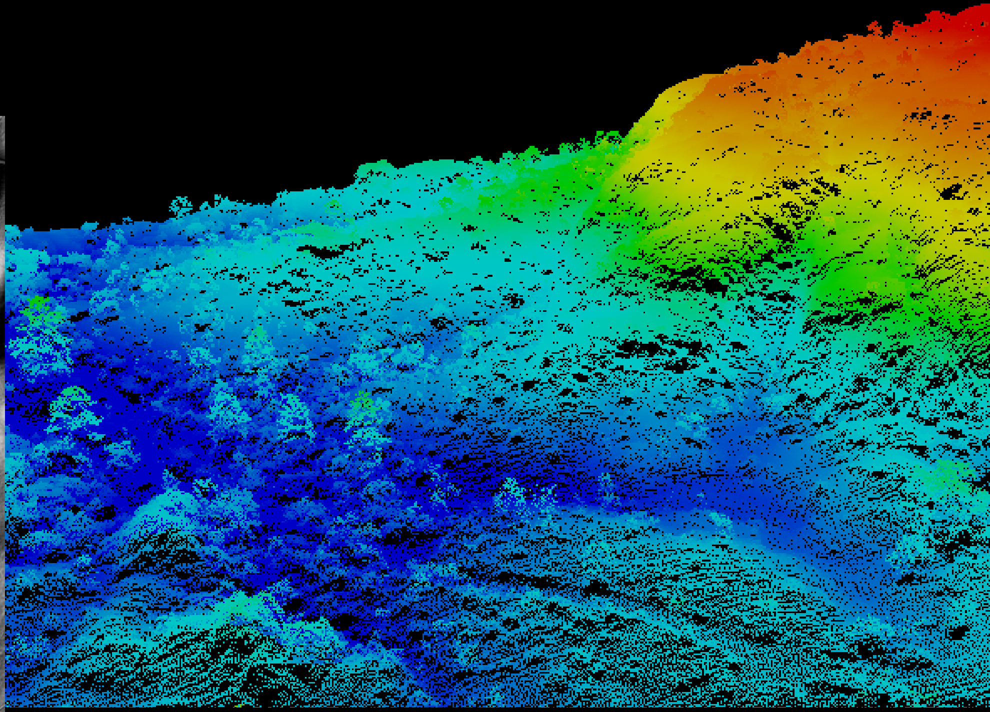
Sharpening our view of earth processes with high resolution topography



Sunset Crater Arizona hillshade (US NPS)



Granite Dells AZ point cloud (NCALM student seed grant)

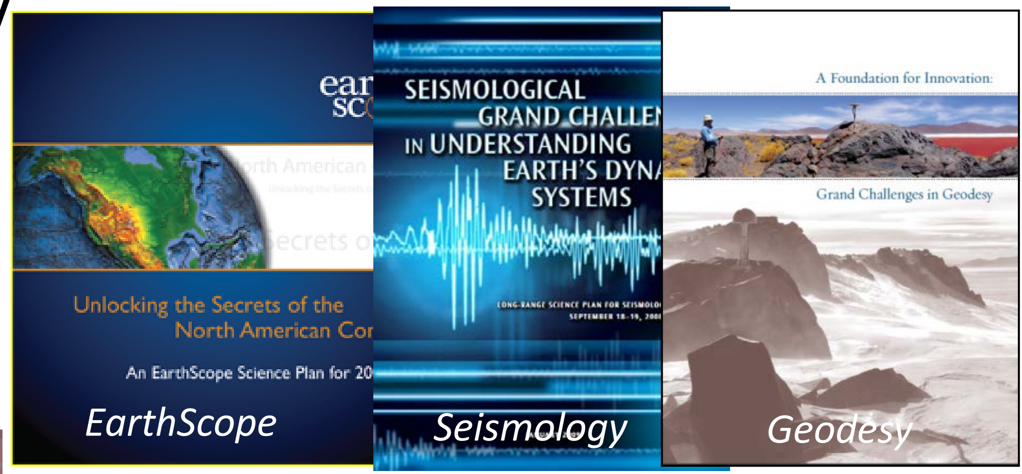
Presentation outline

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

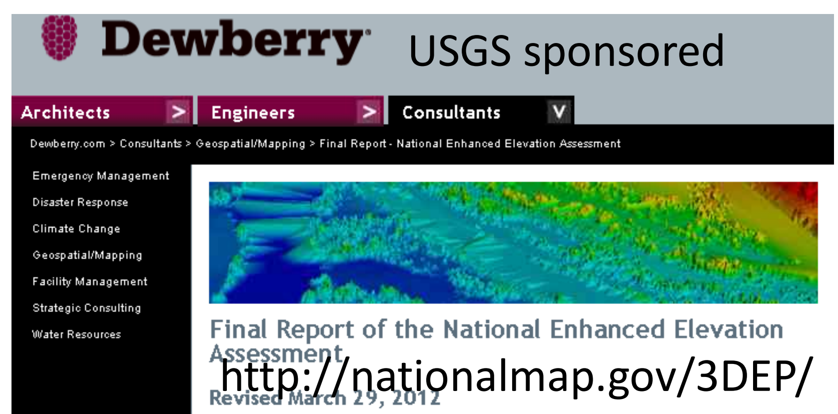
Main Application types

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

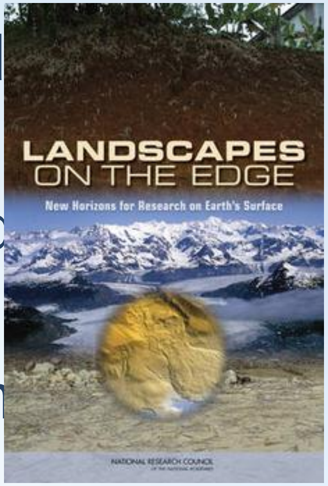
Major US community studies recognize the scientific value of high resolution topography



Science communities

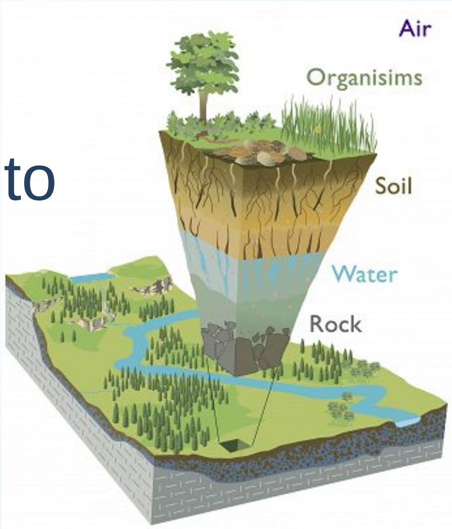


Example scientific motivations



- 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?

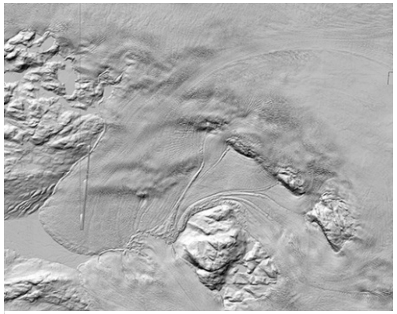


- Coupled hydrogeomorphic-ecosystem response to natural and anthropogenic change
- Landscape and ecosystem dynamics

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

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

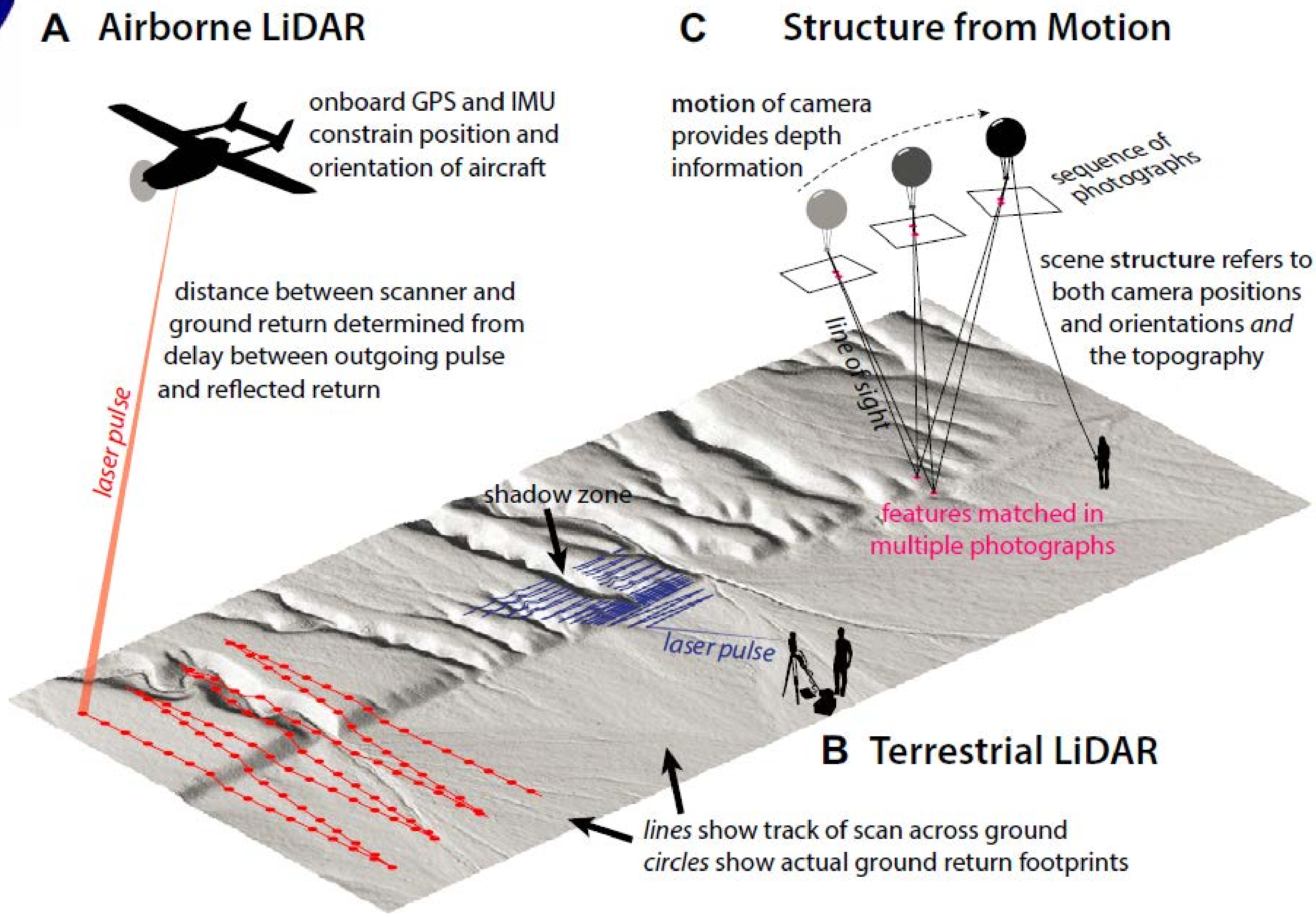
+ASTER



Stereo-Photogrammetric Elevation Model (Polar Geospatial Center)

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

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



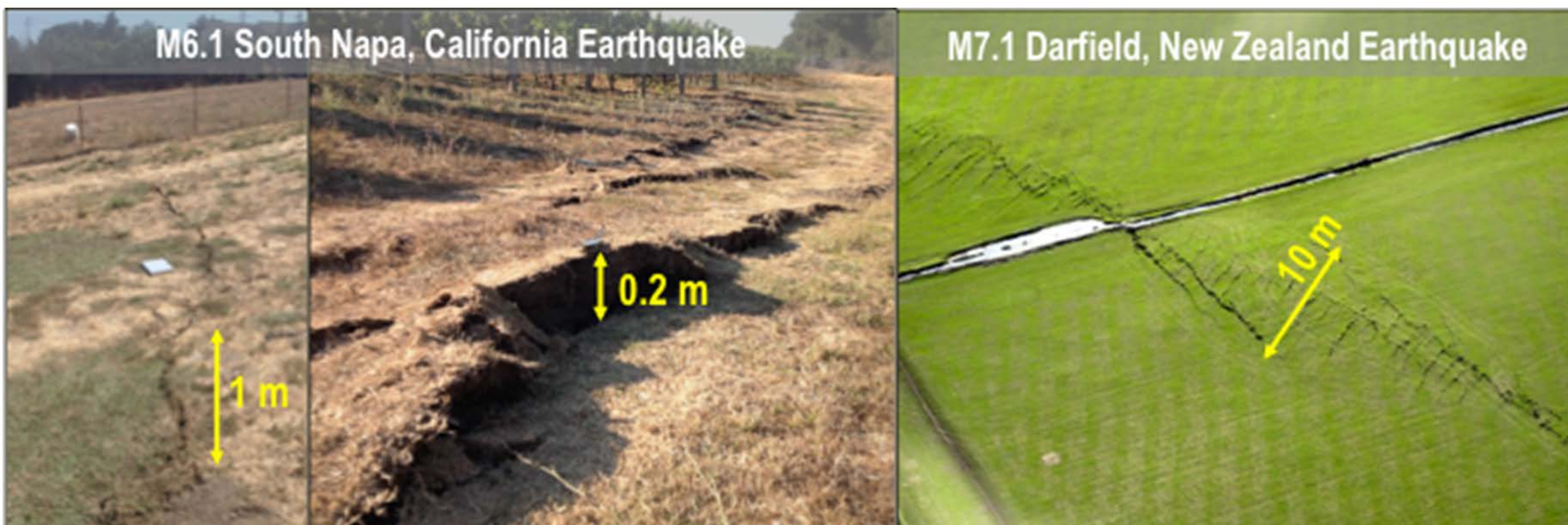
Johnson, K., Nissen, E., Saripalli, S., Arrowsmith, J R., McGarey, P., Scharer, K., Williams, P., Blisniuk, K., Rapid mapping of ultra-fine fault zone topography with Structure from Motion, Geosphere, v. 10; no. 5; p. 1–18; doi:10.1130/GES01017.1, 2014.

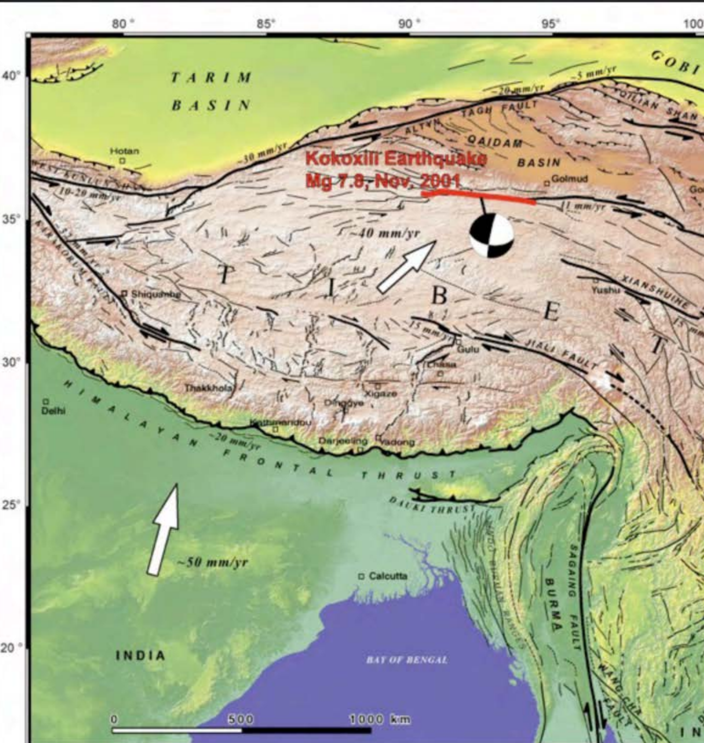
Presentation outline

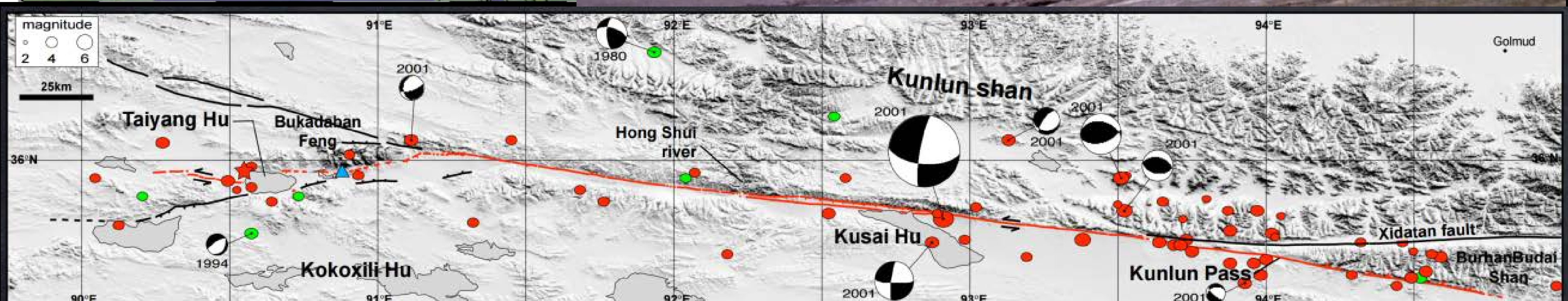
- Introduction and measuring topography
- **“Seeing” and working at the appropriate scale**
- Applications

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





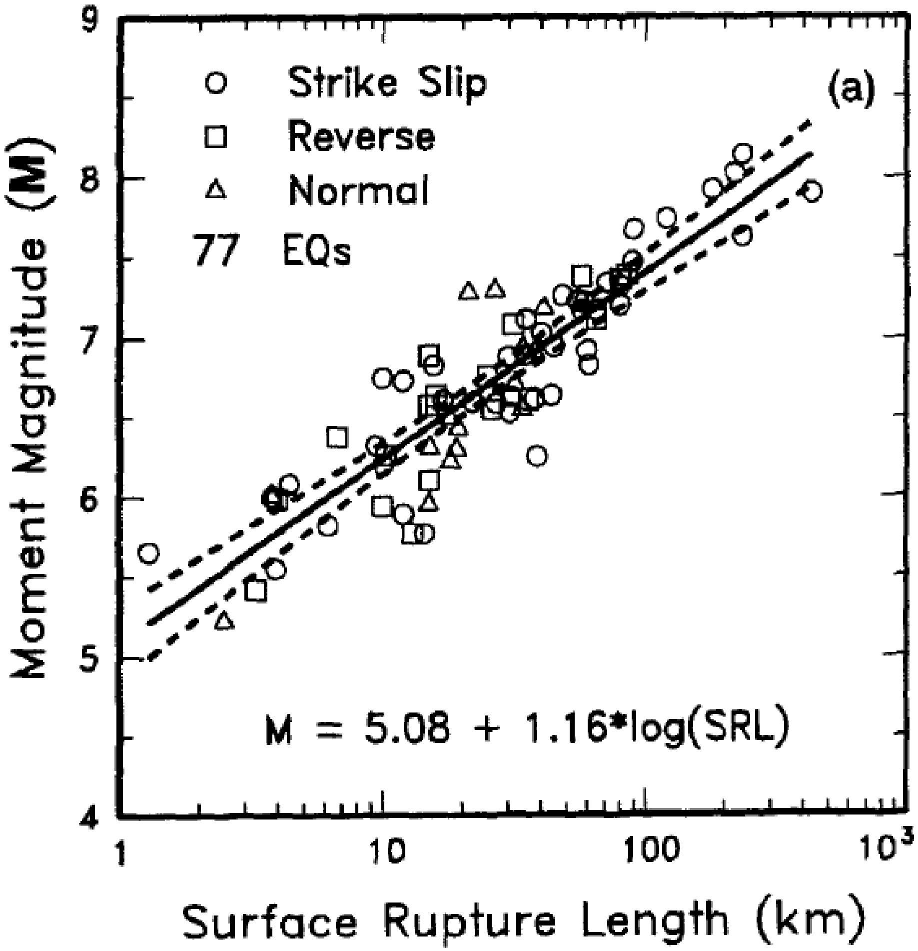



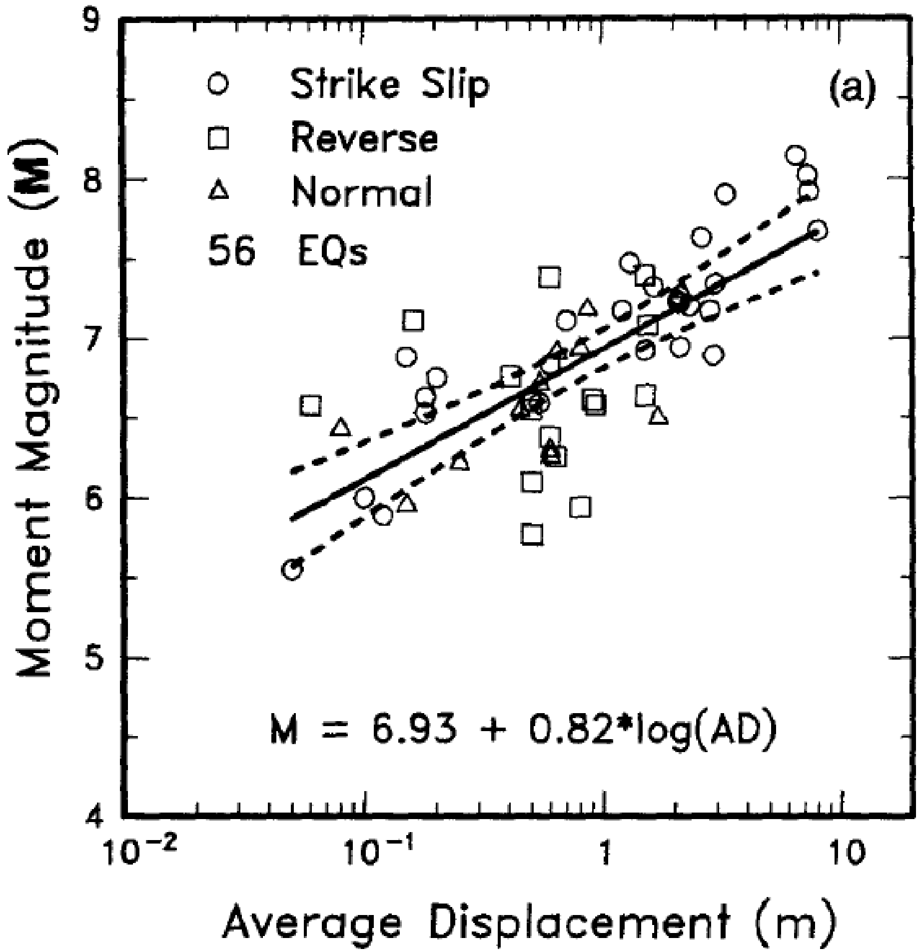
430km of ground rupture, above 4000m

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

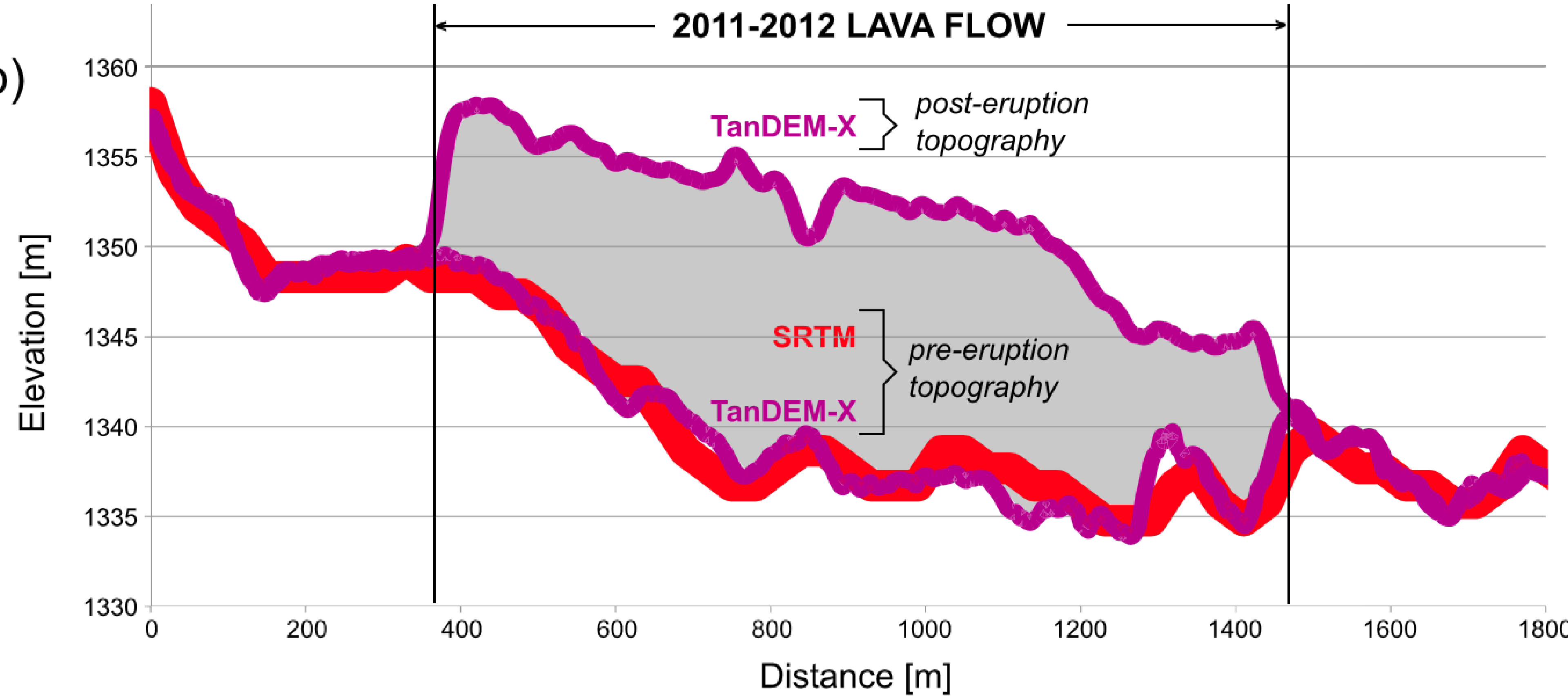
Length scales >10^5m and <1 m

Wells and Coppersmith, 1994





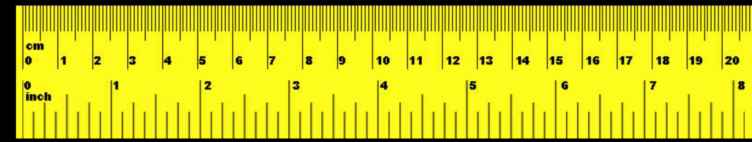
For differencing, need pre-event data



High-resolution TanDEM-X DEM: An accurate method to estimate lava flow volumes at Nyamulagira Volcano (D. R. Congo)

Albino, et al., 2015

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



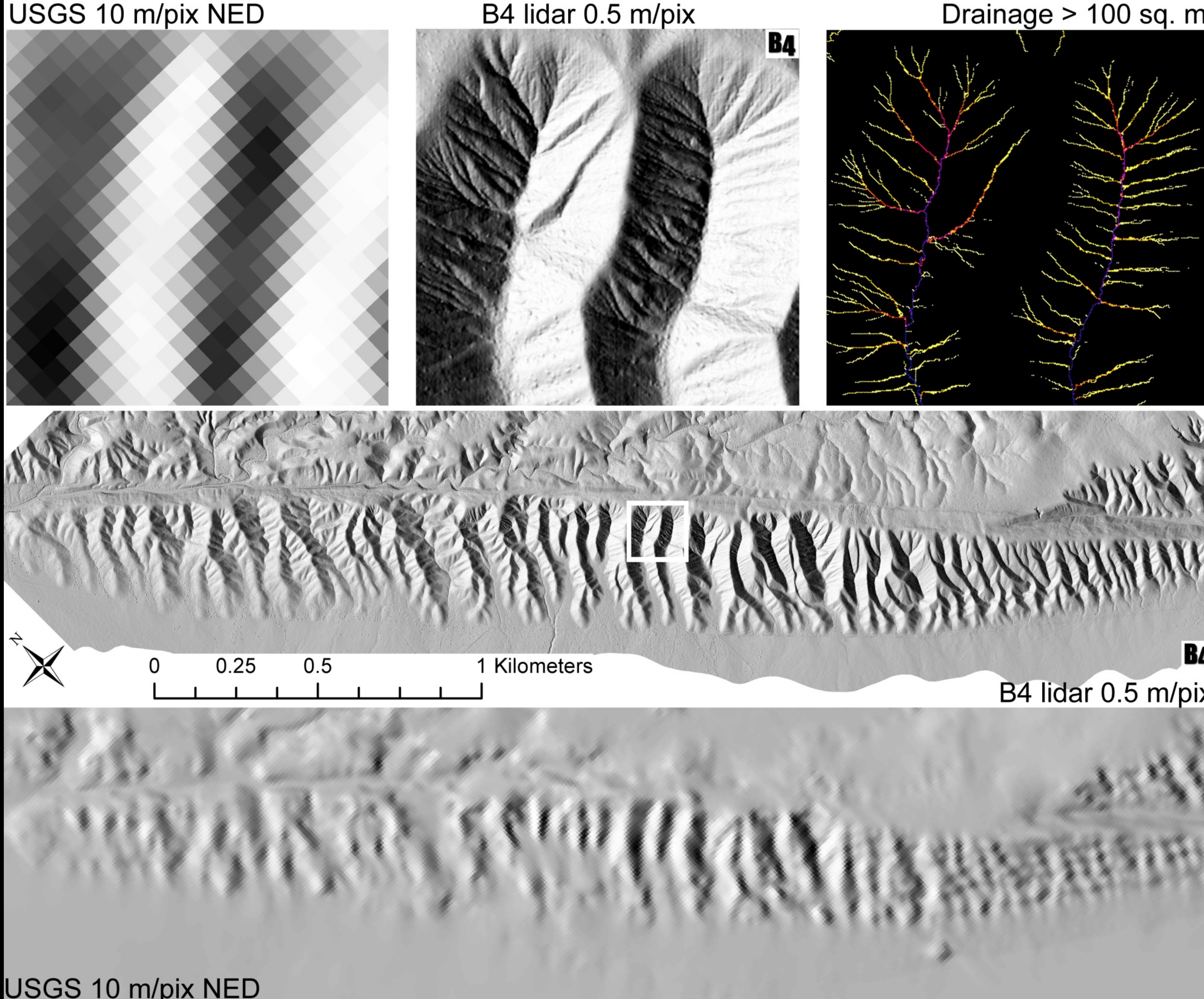
Surface processes act to change elevation through erosion and deposition while tectonic processes depress or elevate the surface directly— their record is best characterized with the right fine scale.

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

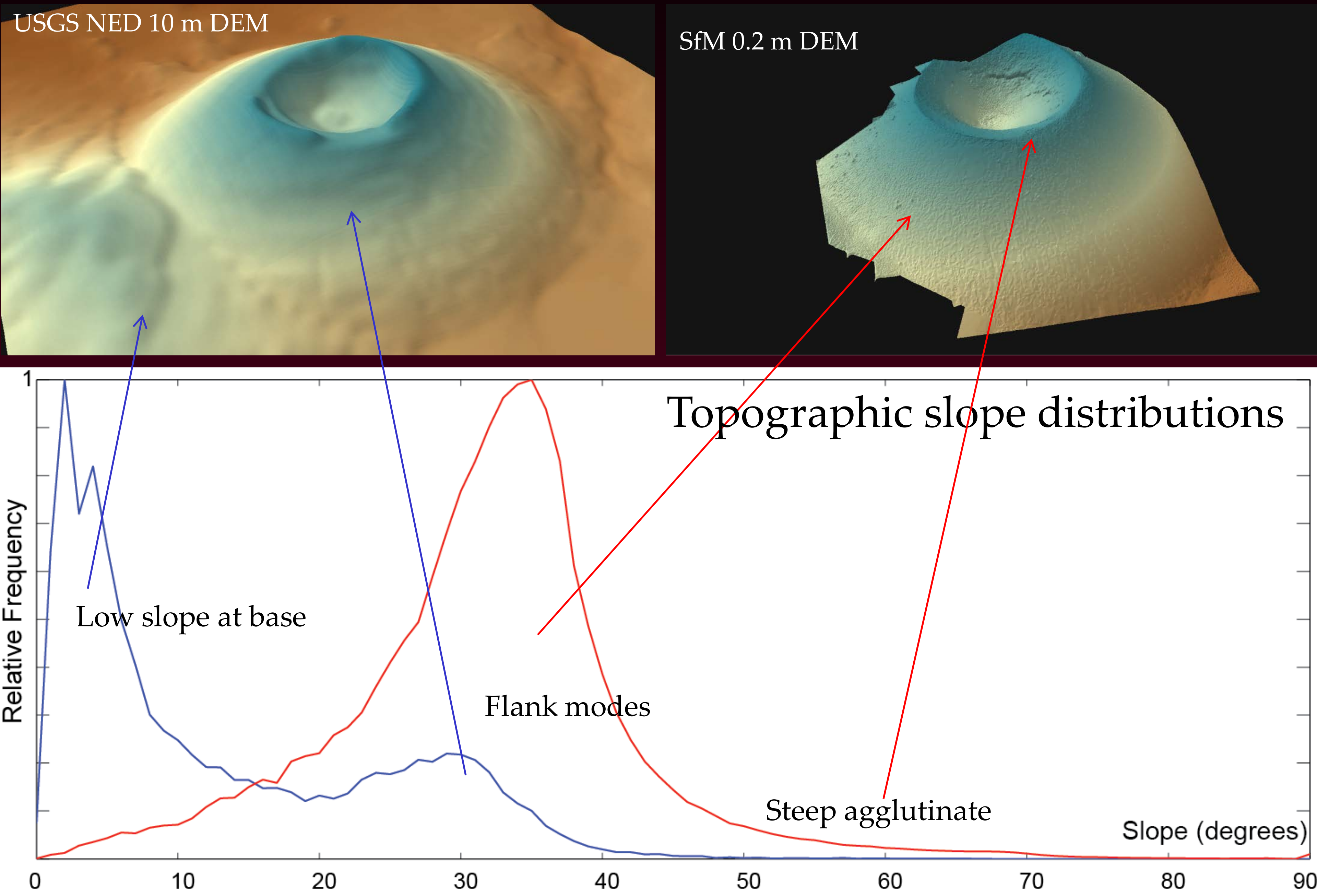
http://en.wikipedia.org/wiki/How_Long_Is_the_Coast_of_Britain%3F_Statistical_Self-Similarity_and_Fractional_Dimension

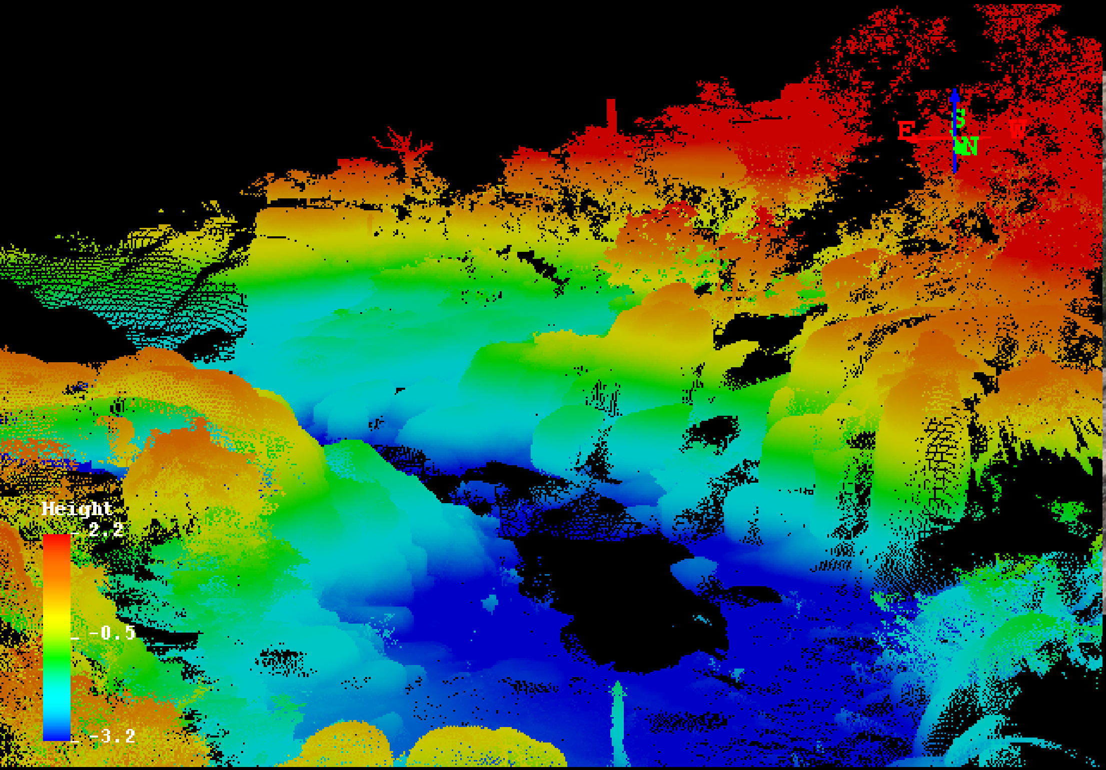
B. B. Mandelbrot



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

Cinder cone slope analysis





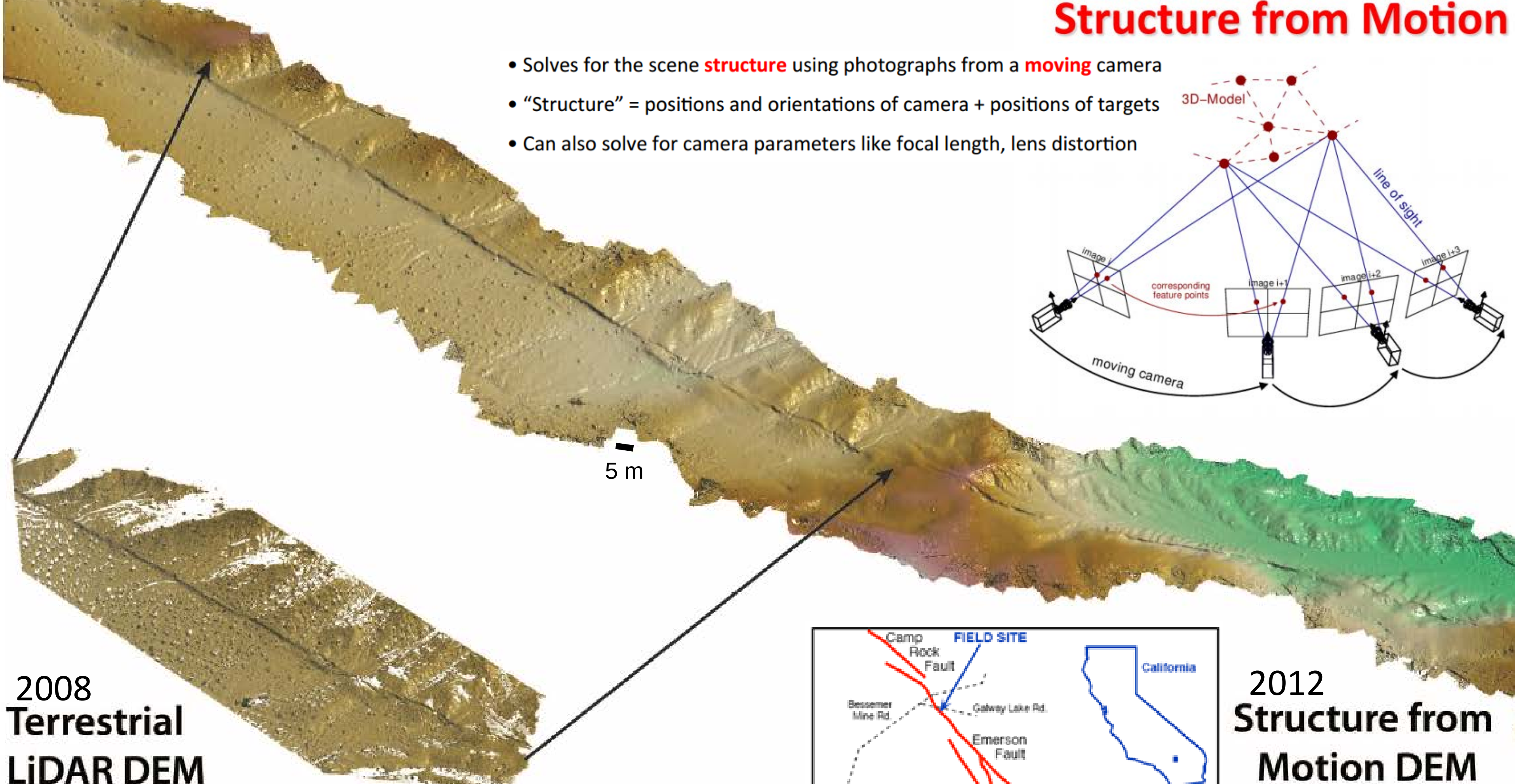
Granite Dells AZ point cloud (Haddad, et al. 2012)

UNAVCO Terrestrial Laser Scanner

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

Structure from Motion

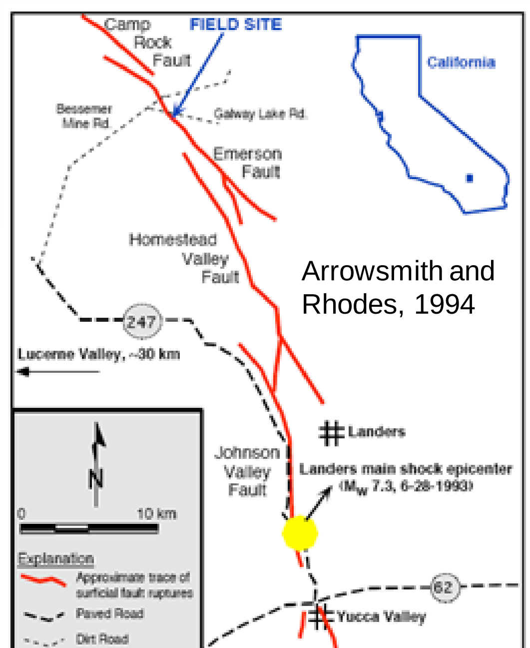
- Solves for the scene **structure** using photographs from a **moving** camera
- “Structure” = positions and orientations of camera + positions of targets
- Can also solve for camera parameters like focal length, lens distortion



2008
Terrestrial LiDAR DEM
Haddad, et al., 2012

2012
Structure from Motion DEM
Johnson, et al. 2014

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



Arrowsmith and Rhodes, 1994

Main Application types

- **Feature mapping at fine scale**
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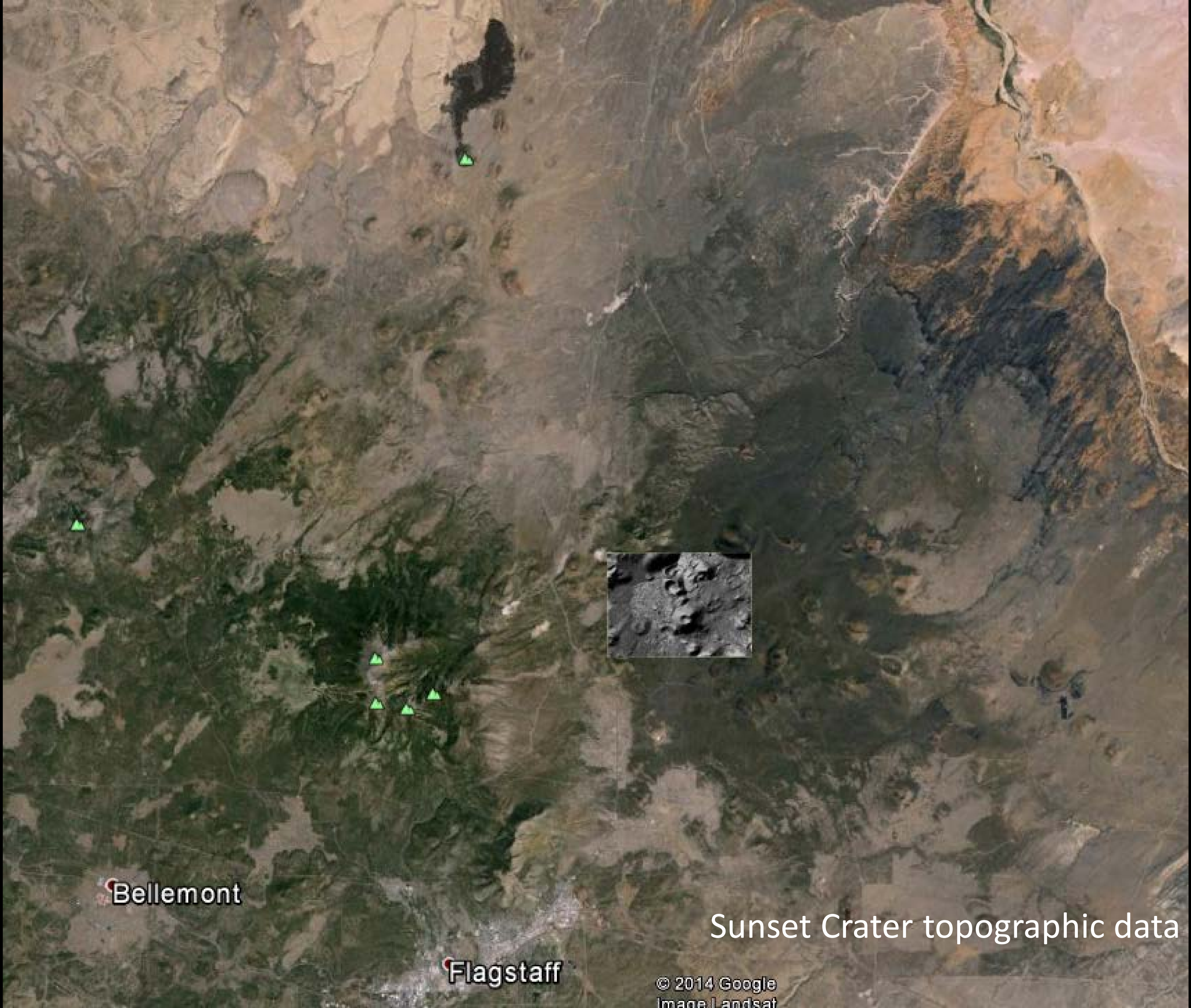
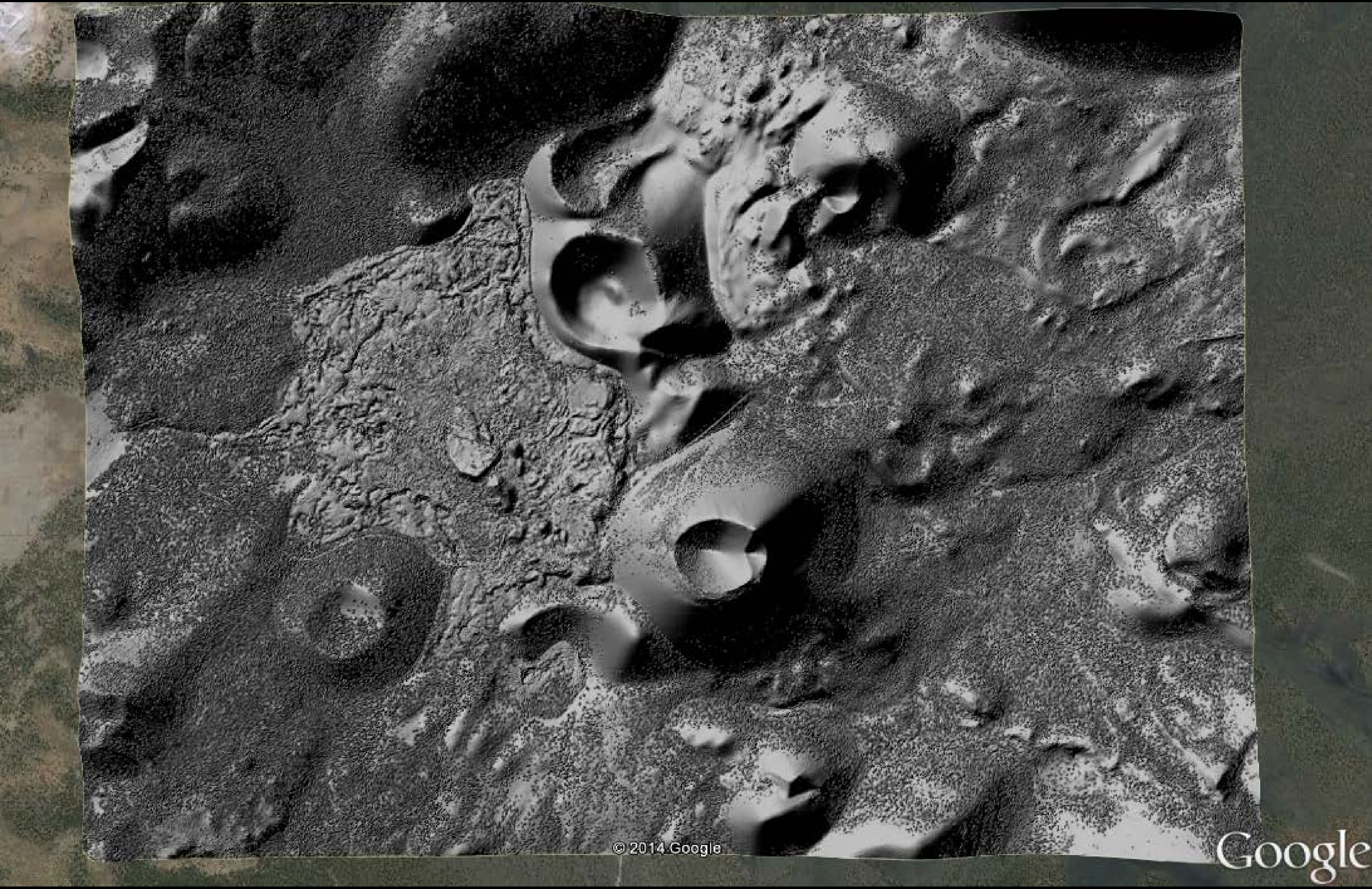
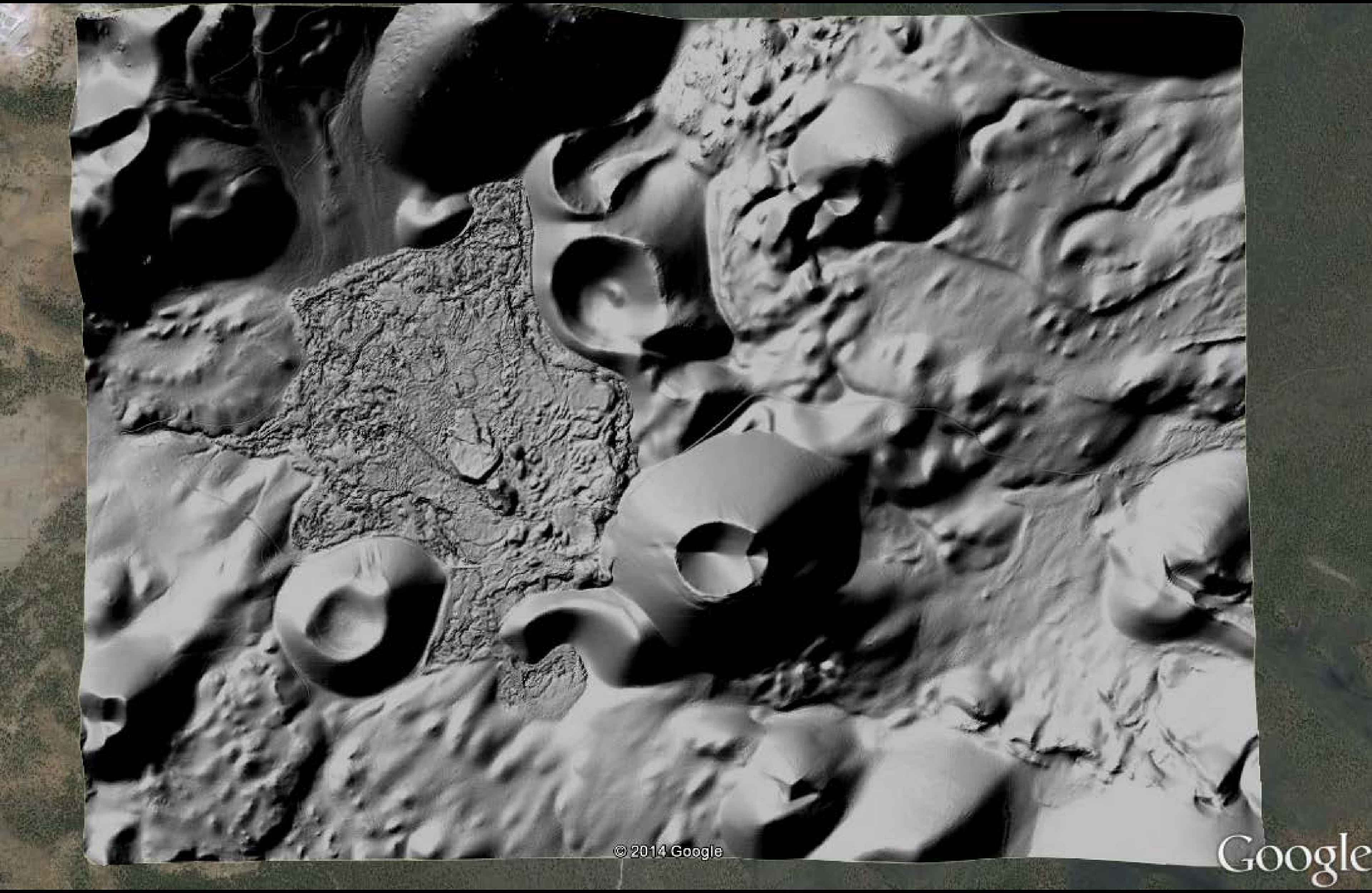


Sunset Crater topographic data


© 2014 Google
Google


© 2014 Google
Google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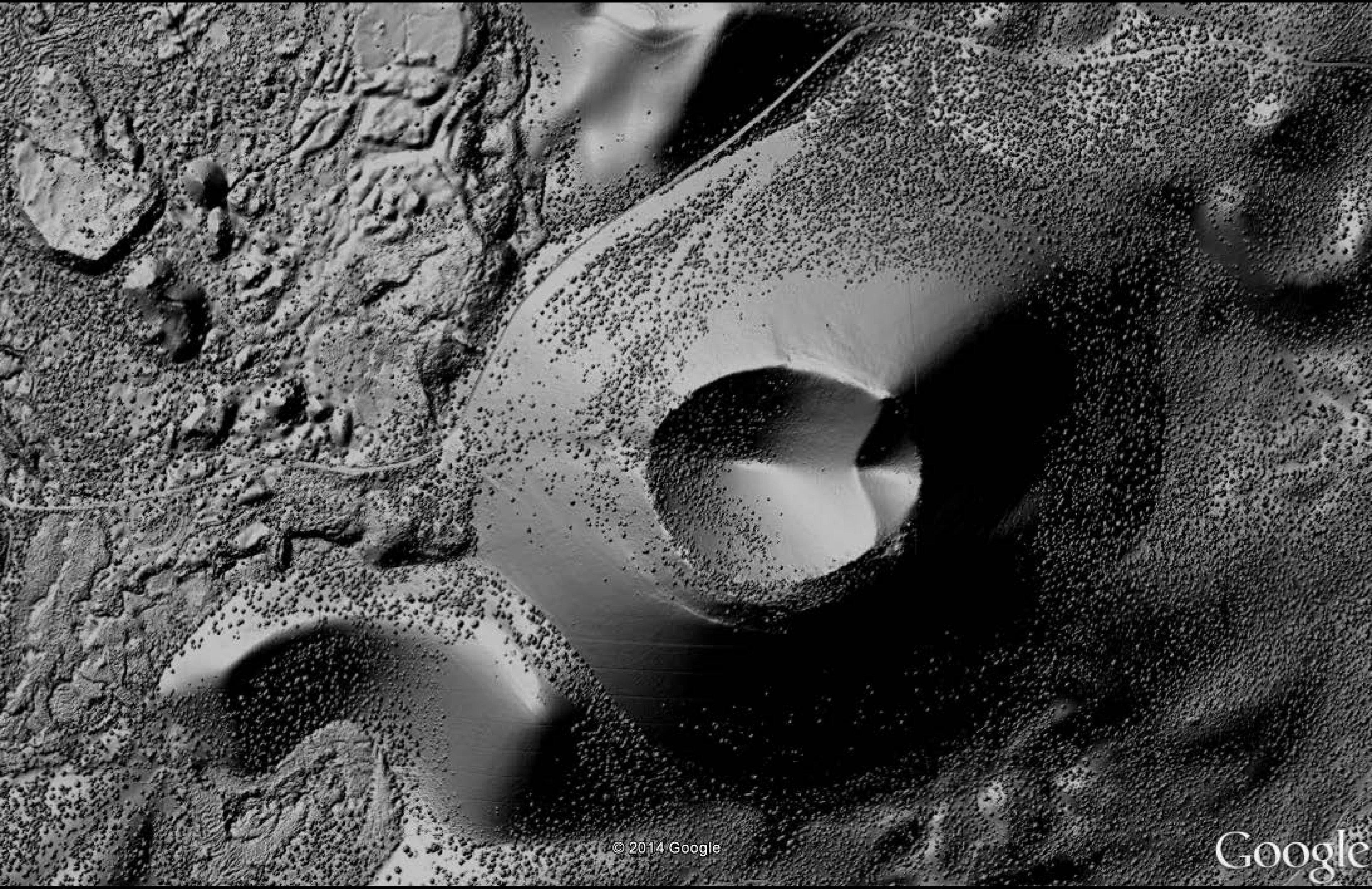
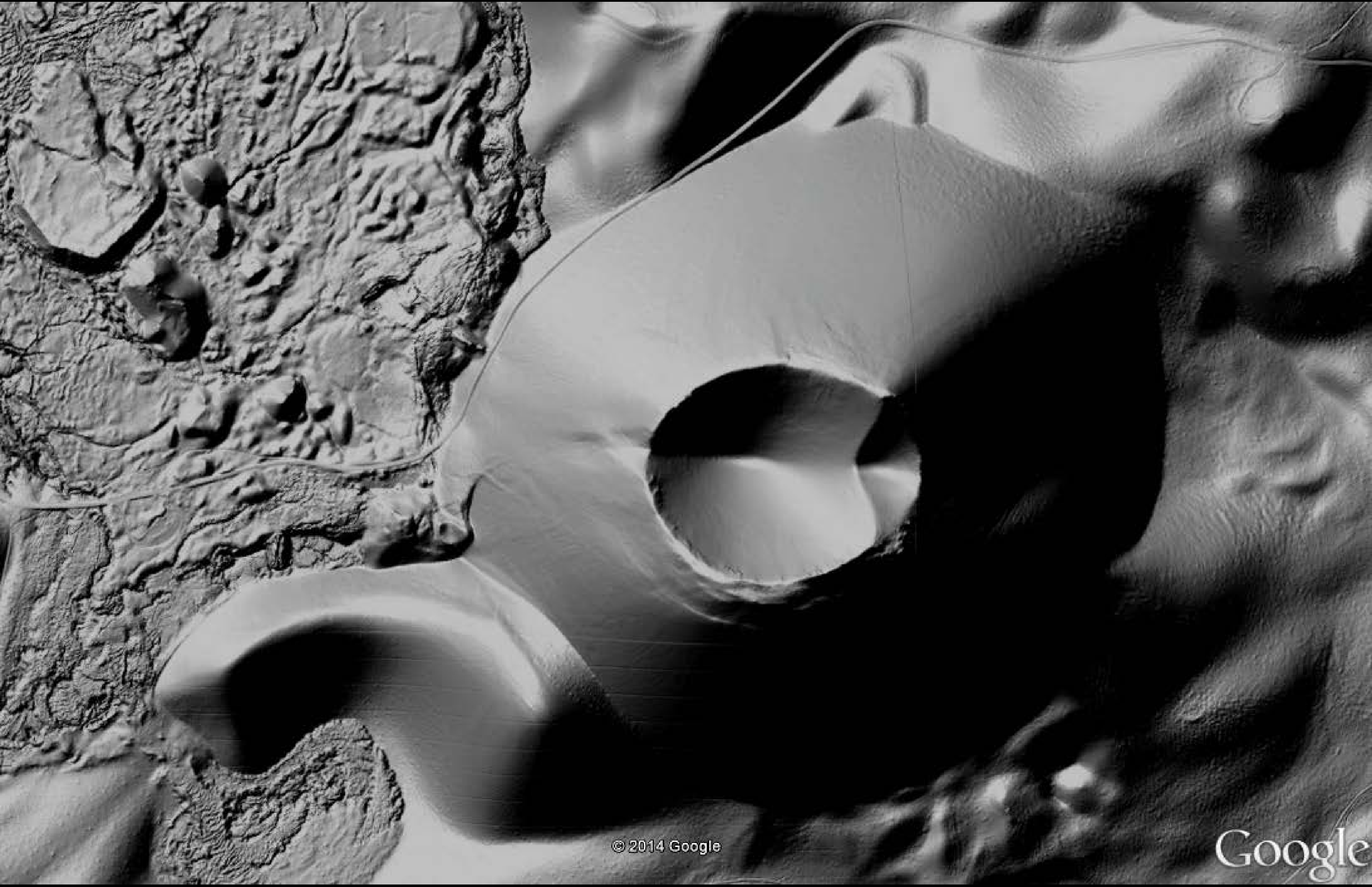
Lidar: full feature (all returns)



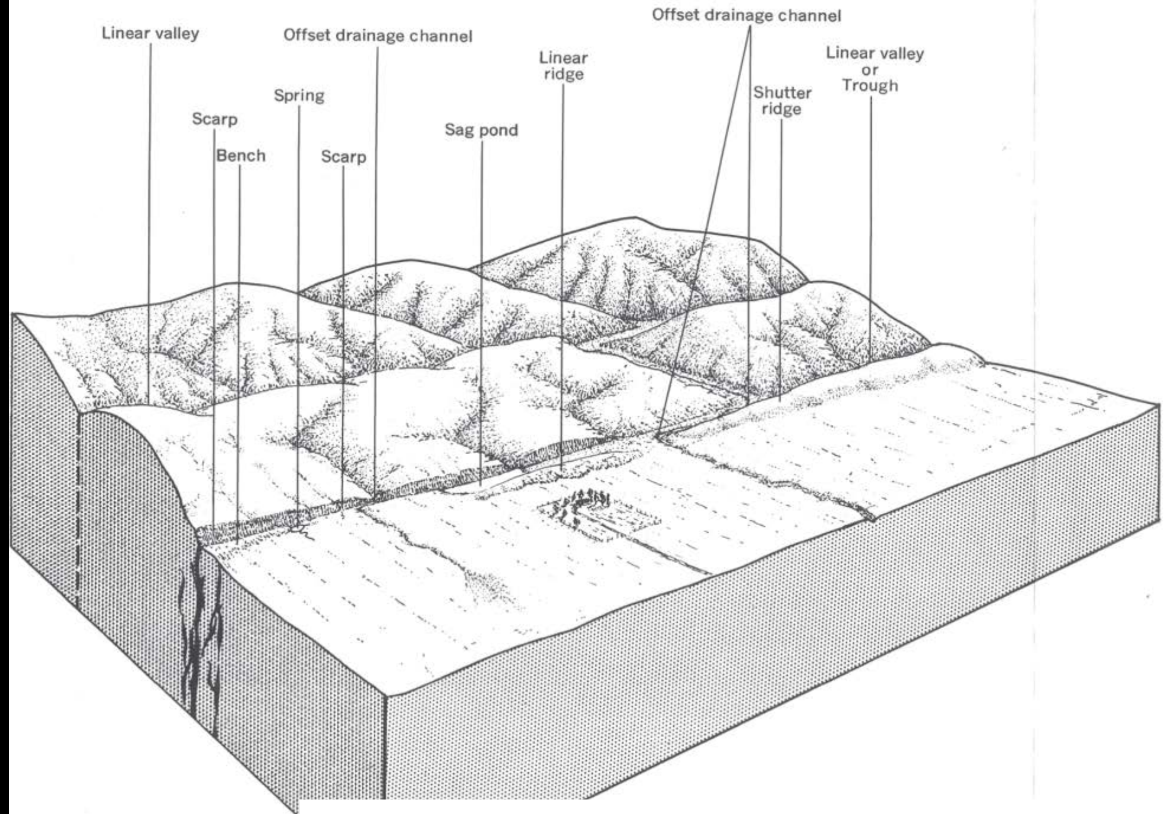
Lidar: bare earth



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

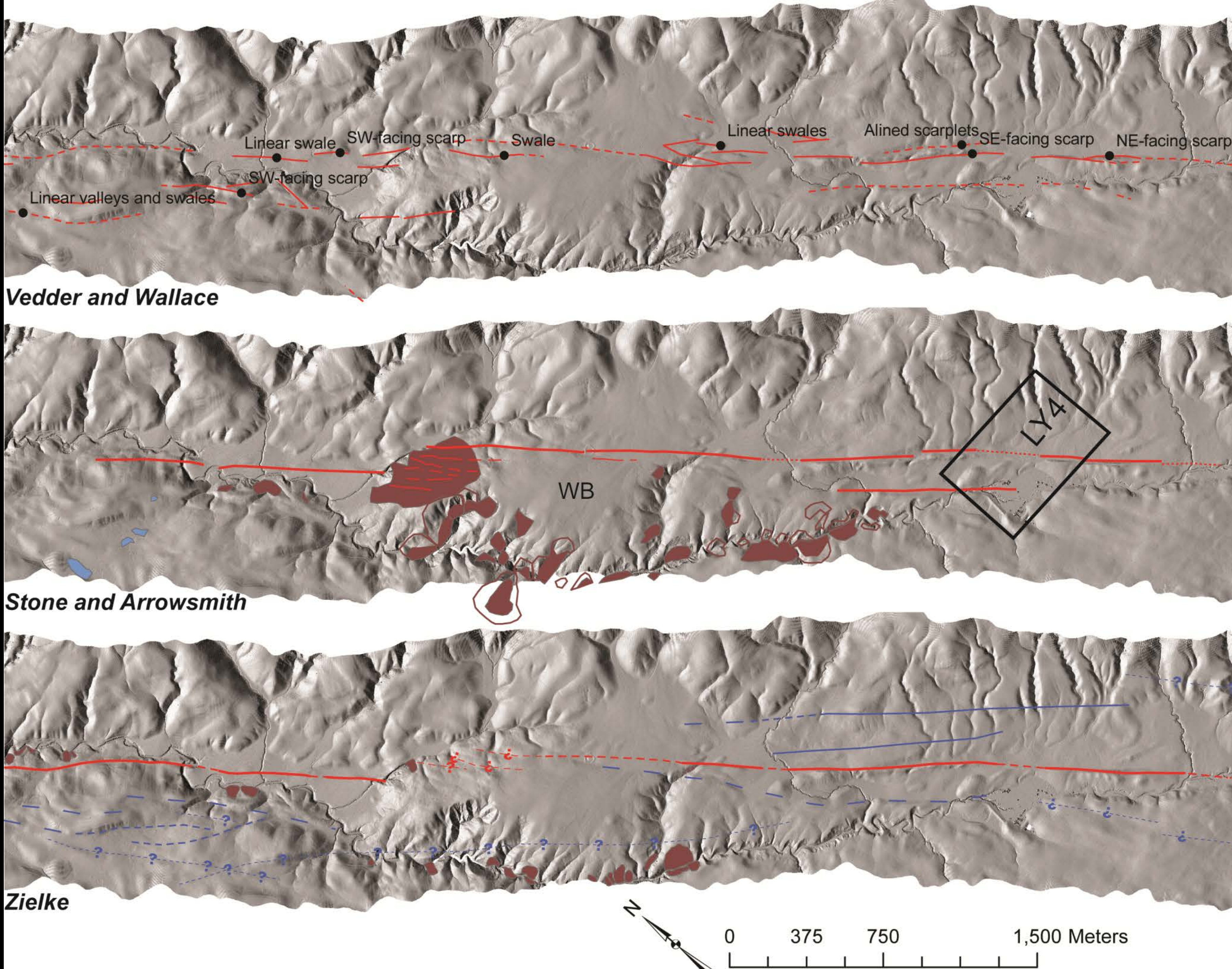
Stone and Arrowsmith

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

Zielke, this study

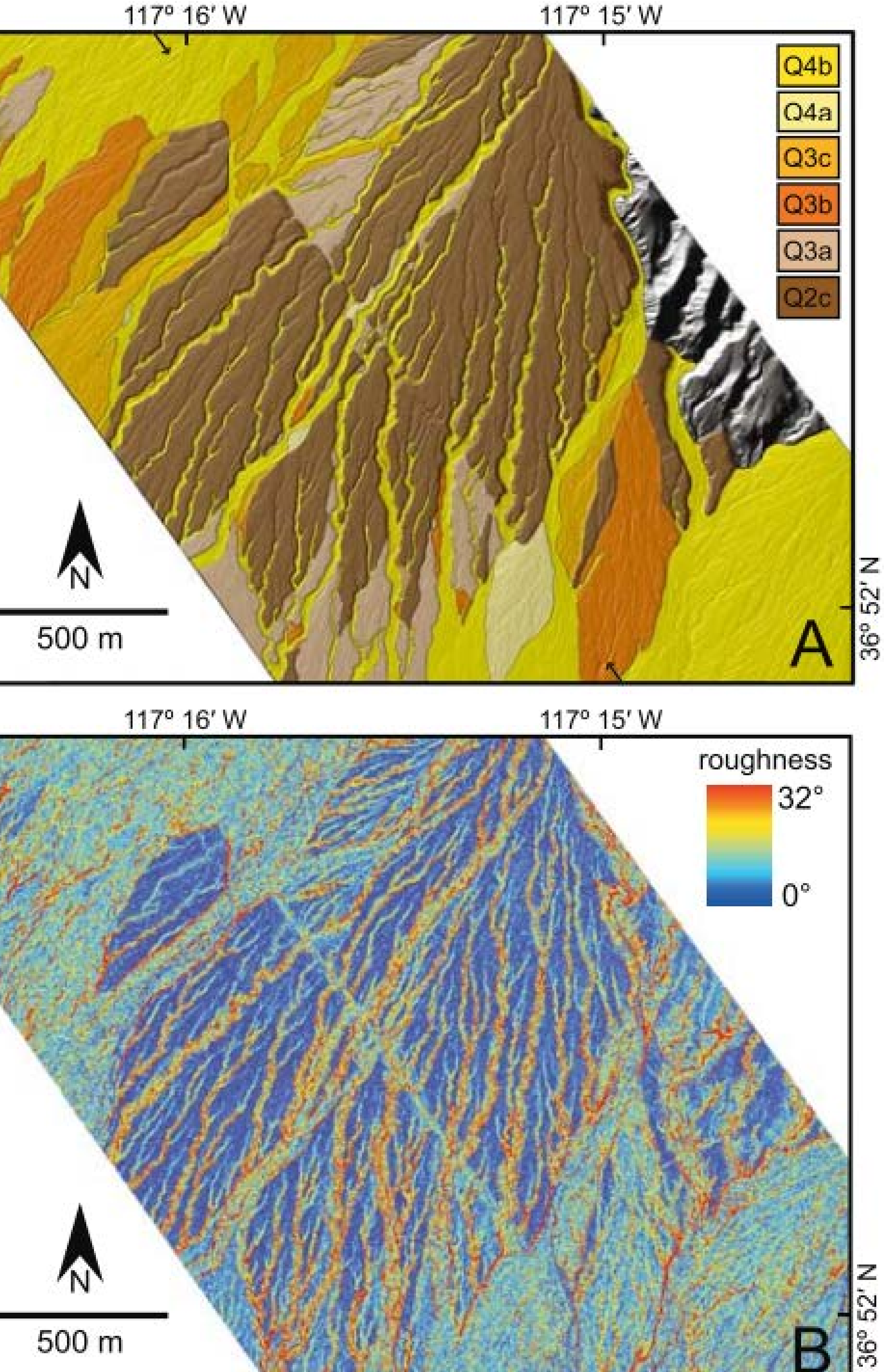
Fault traces: red for main trace, blue for secondary traces

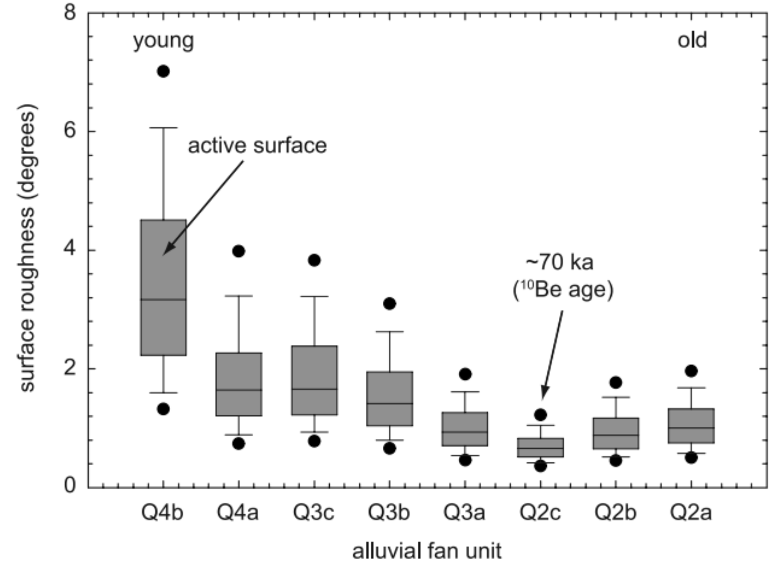
- Fault trace, certain
- Fault trace, inferred
- ? Fault trace, queried
- Fault trace, uncertain
- Landslide deposit and scarp



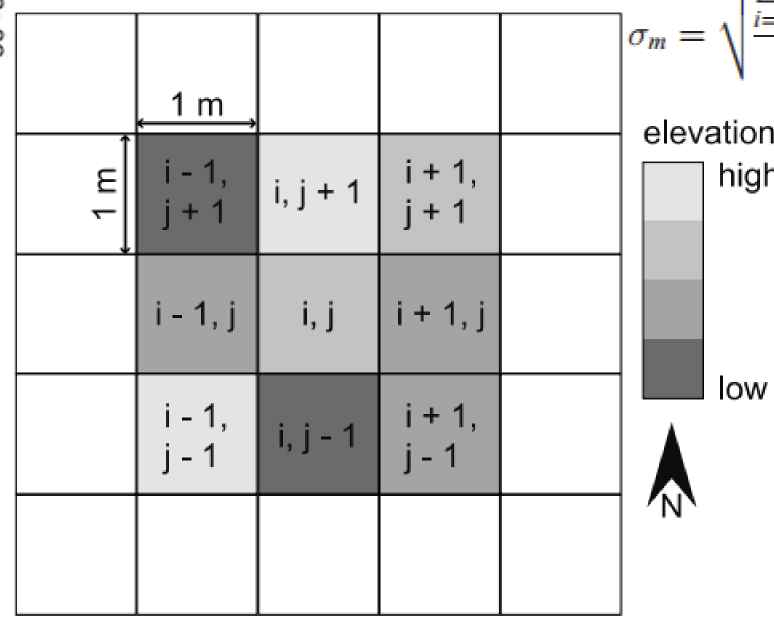
Linear swale
SW-facing scarp
Swale
Linear swales
Alined scarplets
SE-facing scarp
NE-facing scarp
SW-facing scarp
Linear valleys and swales
Vedder and Wallace
LY4
WB
Stone and Arrowsmith
Zielke
N
0
375
750
1,500 Meters

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



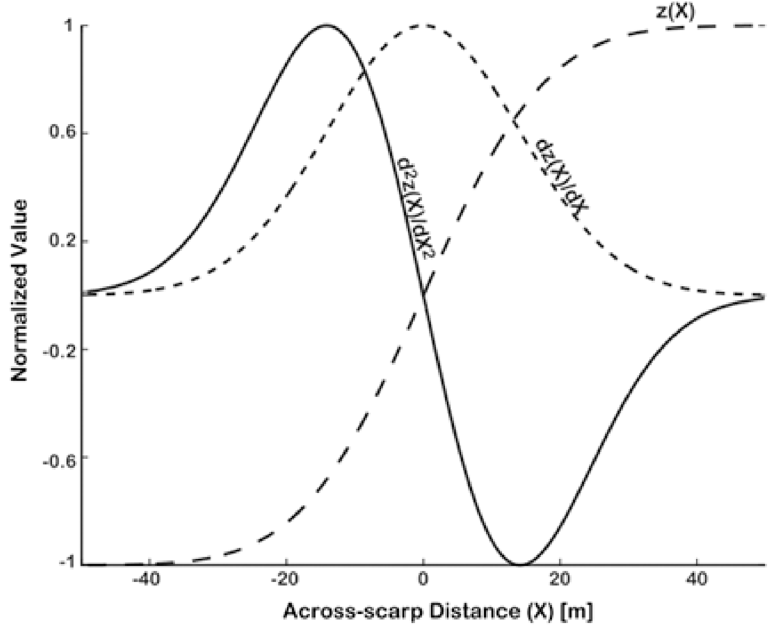


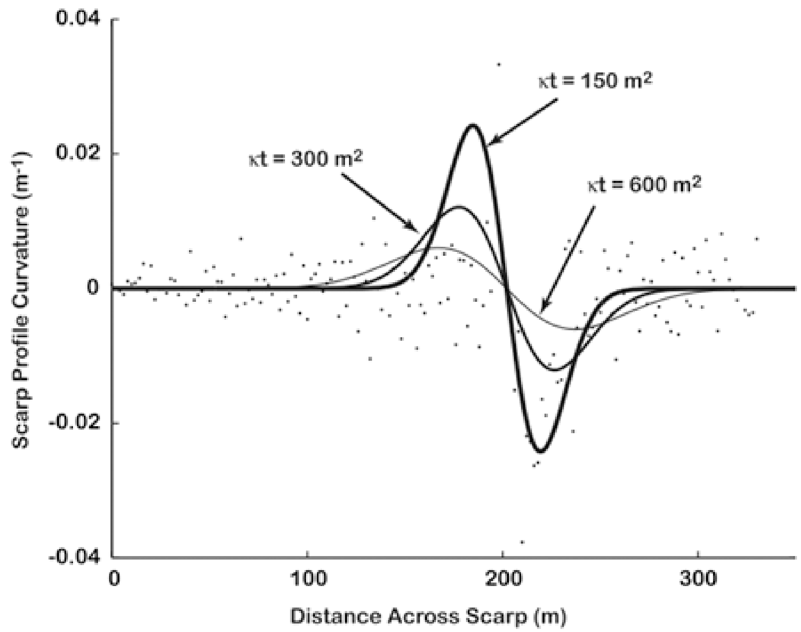
$$\sigma_m = \sqrt{\frac{\sum_{i=1}^{n} (m_i - \overline{m})^2}{n}},$$

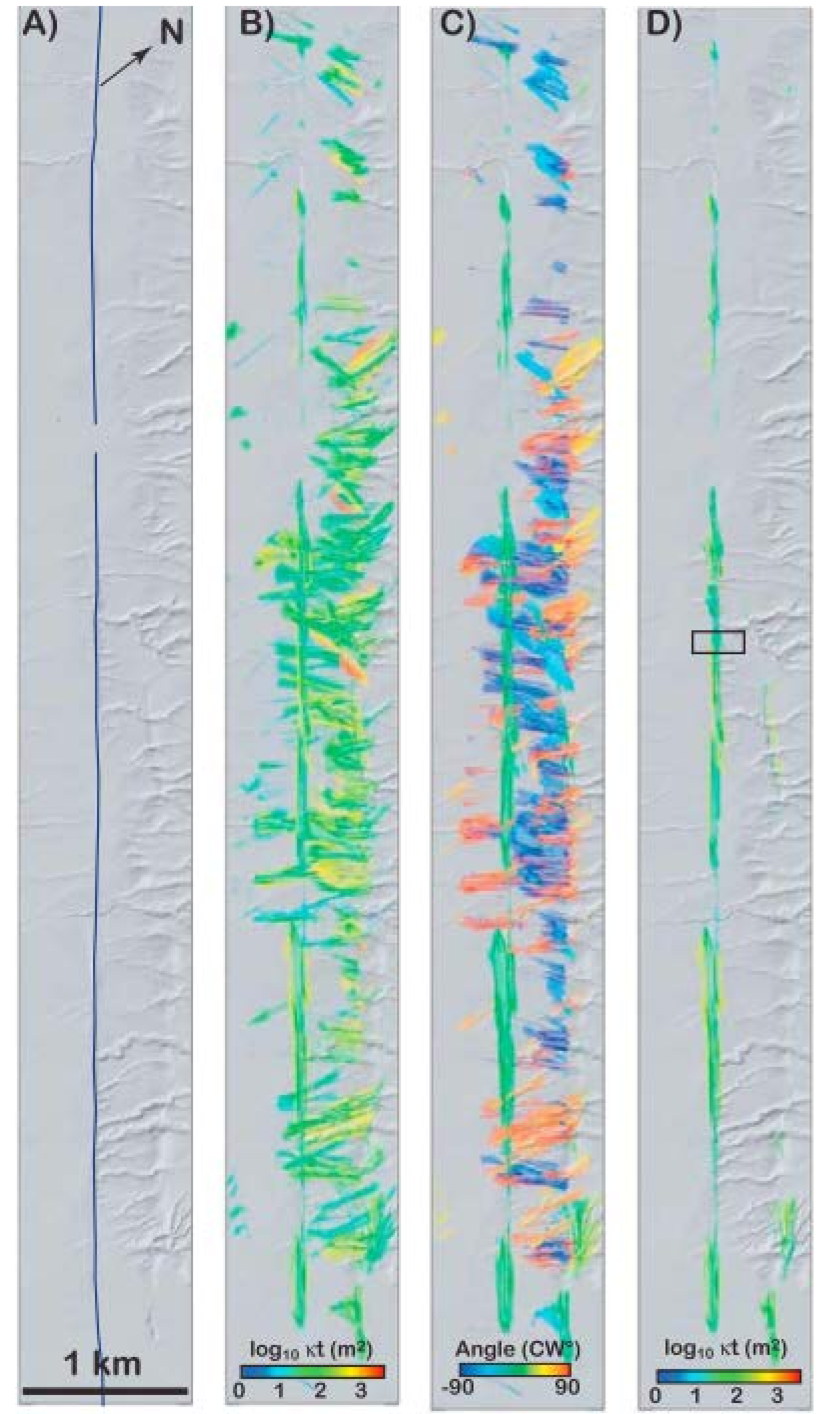


Characterizing arid region alluvial fan surface roughness with airborne laser swath mapping digital topographic data

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







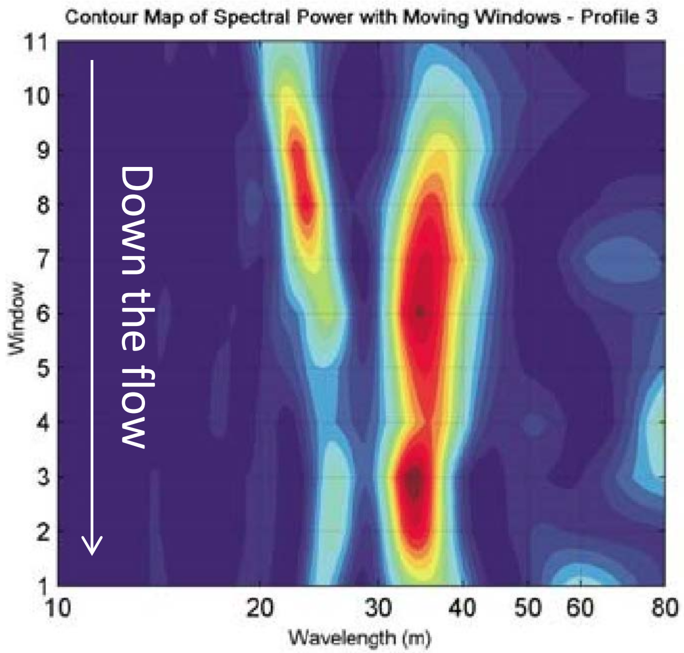
Morphologic dating of fault scarps using airborne laser swath mapping (ALSM) data

GRL, 2010

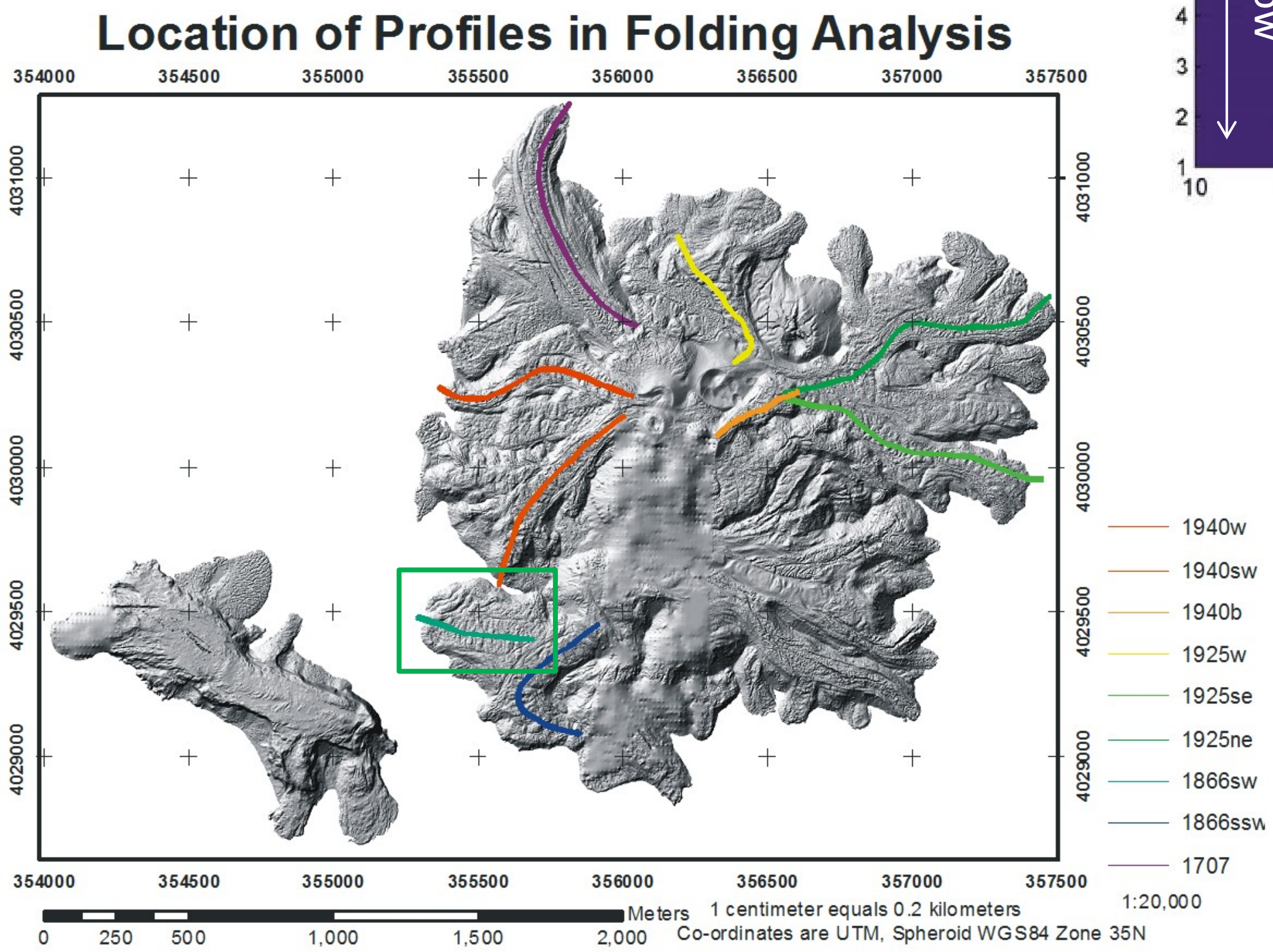
G. E. Hilley,[1] S. DeLong,[2] C. Prentice,[2] K. Blisniuk,[3] and JR. Arrowsmith[4]

Quantitative morphology, recent evolution, and future activity of the Kameni Islands volcano, Santorini, Greece

Pyle and Elliott, Geosphere, 2006



"Buckling with an ~20 m wavelength can be observed near the vent; downstream, a 30–40 m wavelength becomes dominant"



Main Application types

- Feature mapping at fine scale
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- Landscape reconstruction (offsets)
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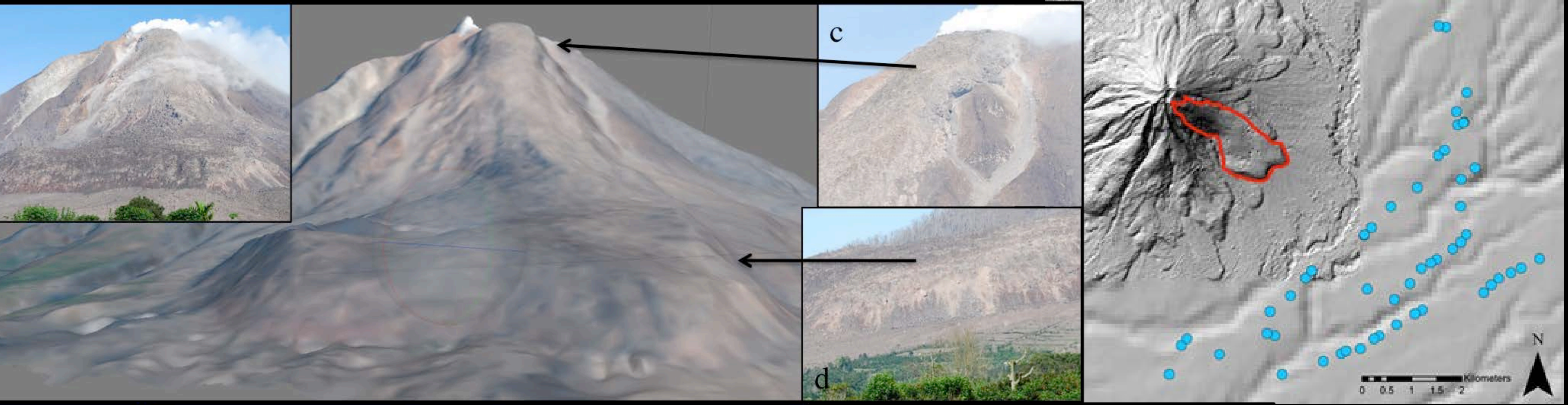
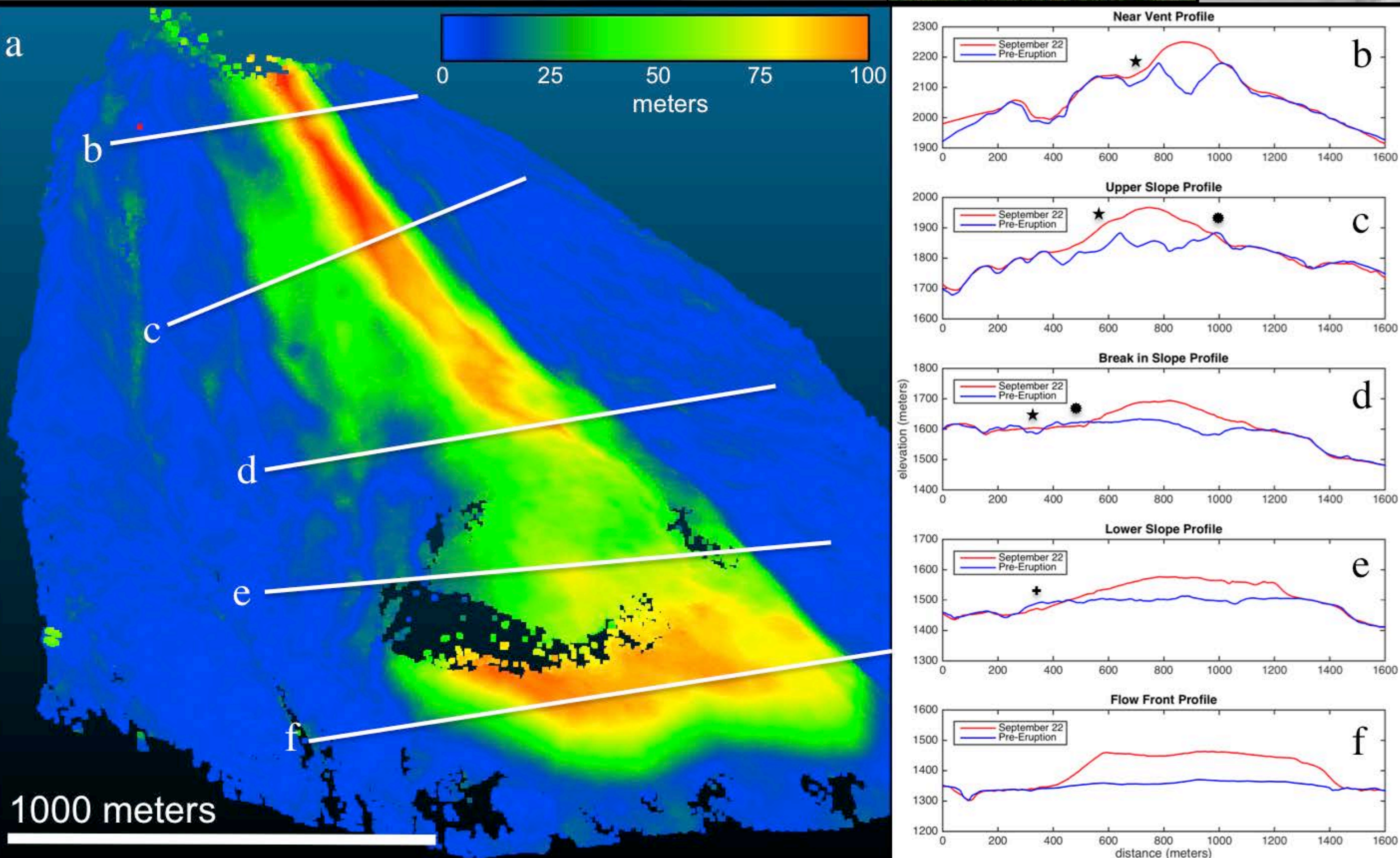
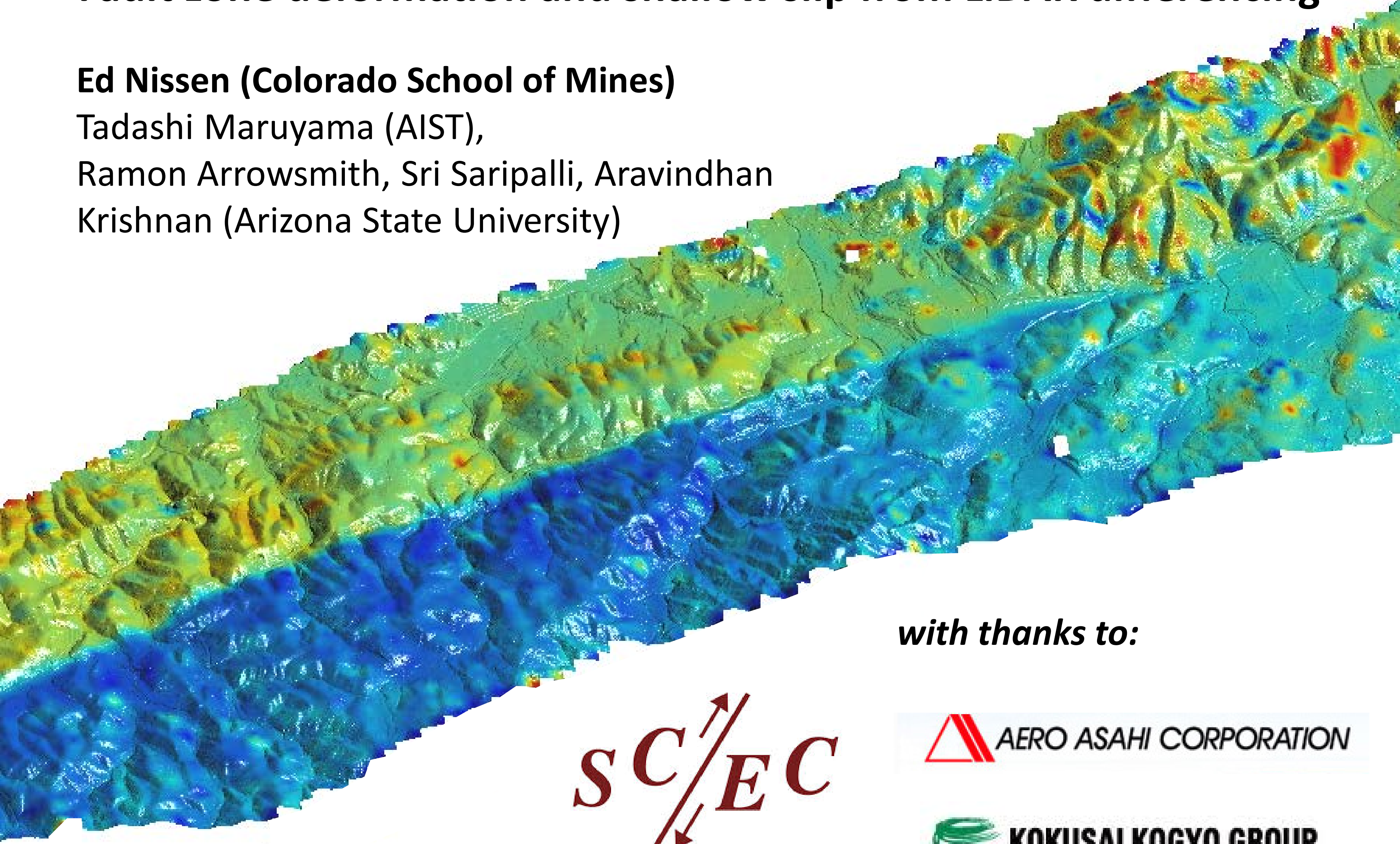




The emplacement of the active lava flow at Sinabung Volcano, Sumatra, Indonesia, documented by structure-from-motion photogrammetry -Carr, et al., in review.

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

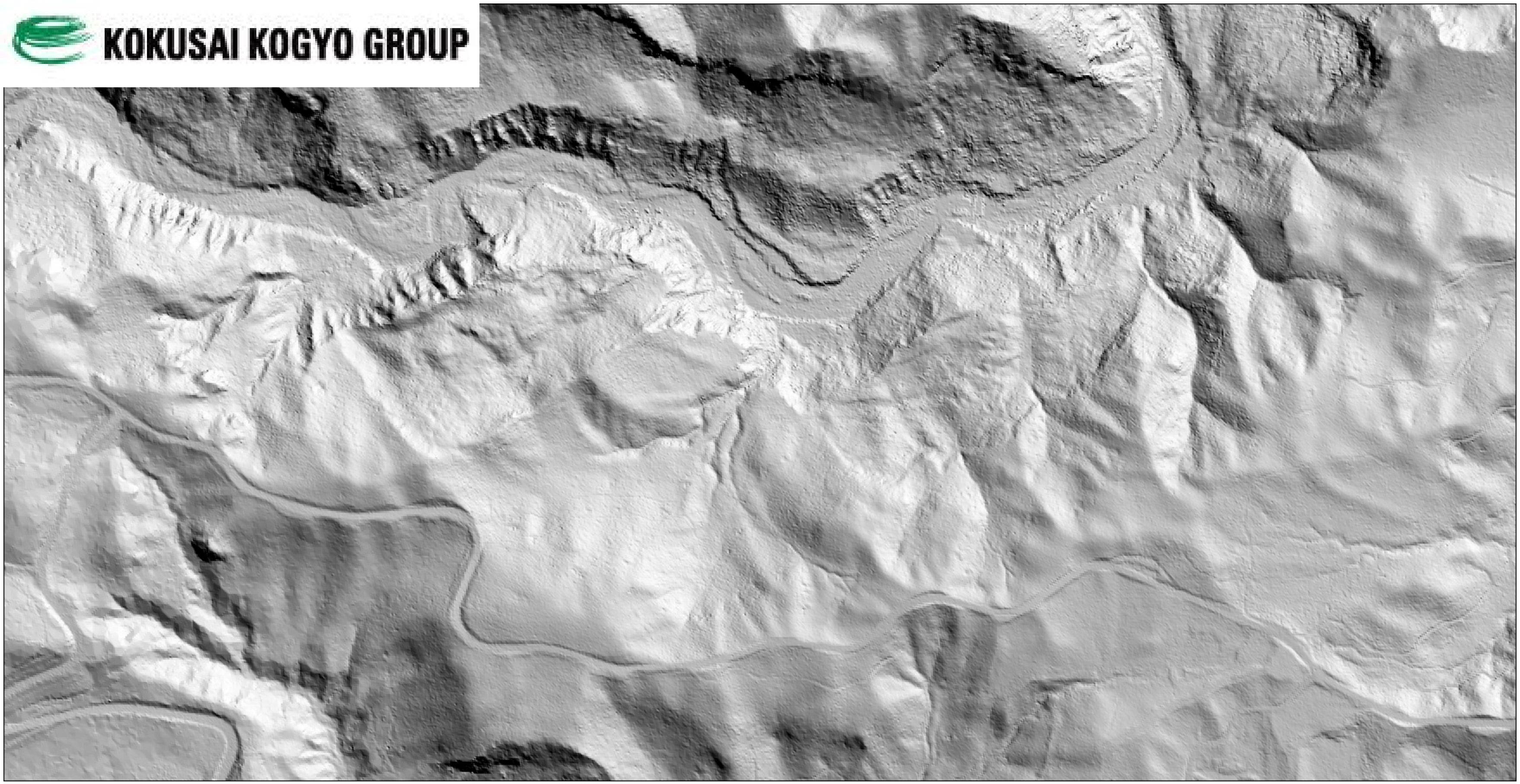
with thanks to:

SCEC
an NSF+USGS center

AERO ASAHI CORPORATION

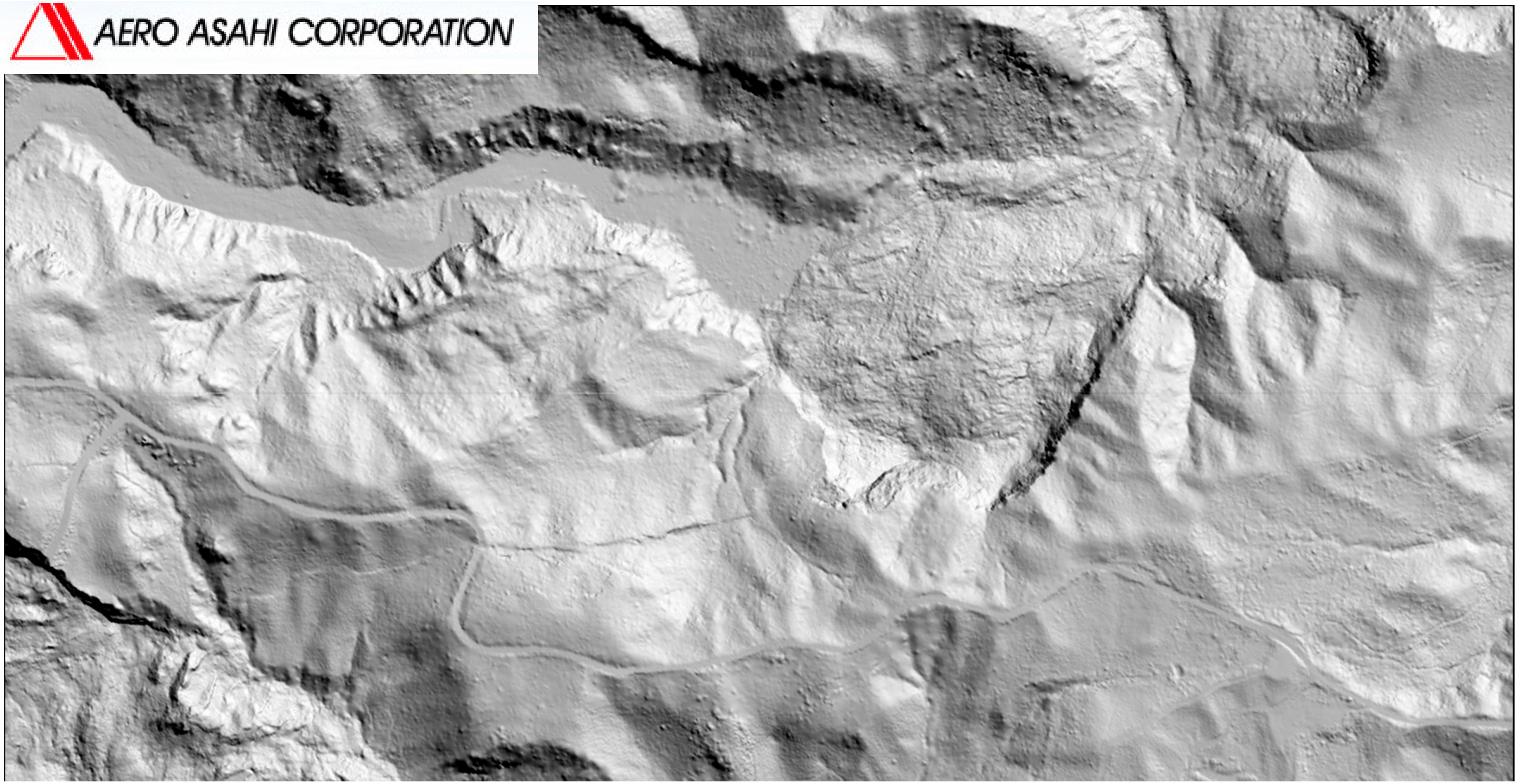
KOKUSAI KOGYO GROUP

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



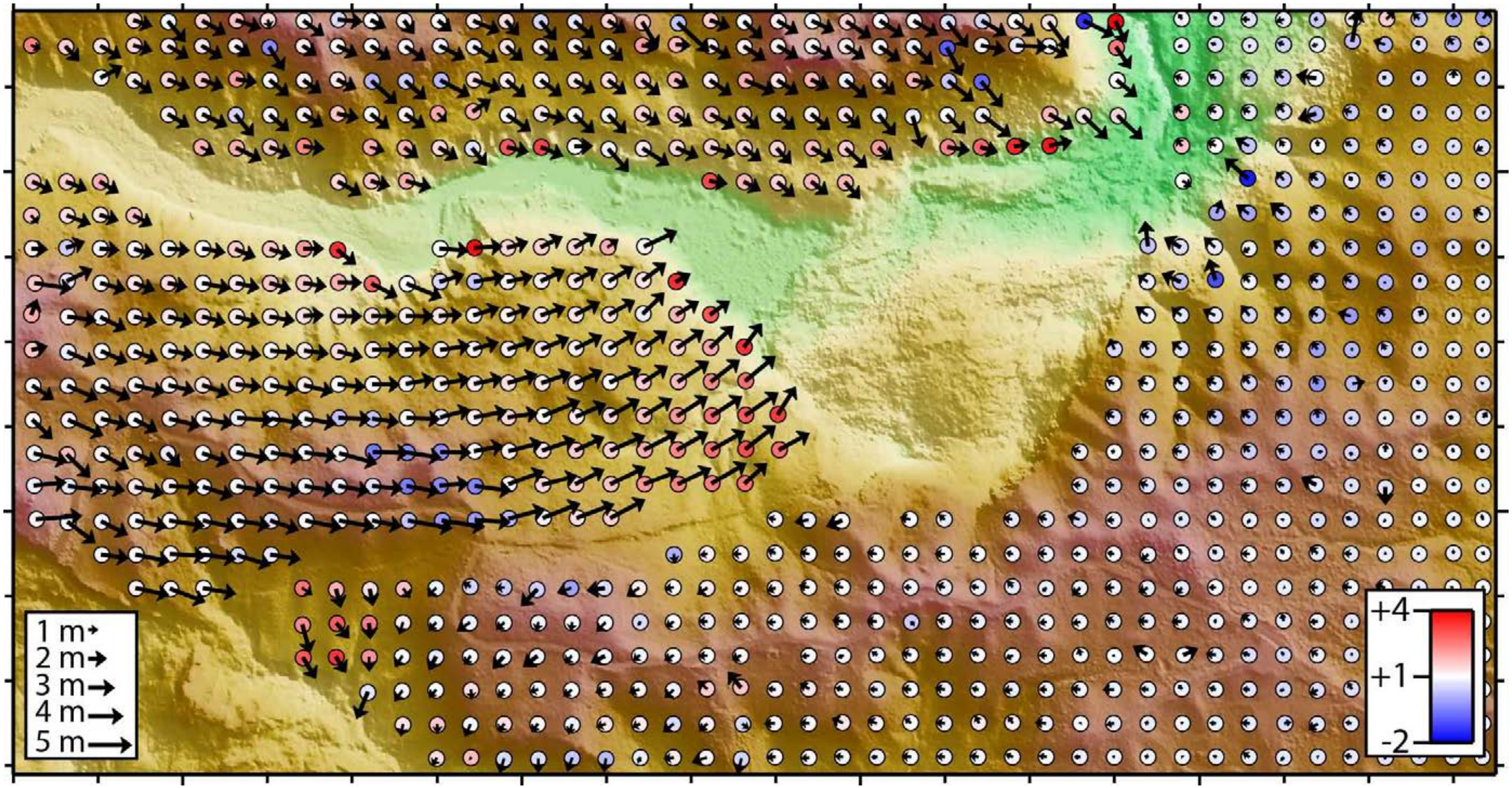
Pre-earthquake DEM (2m)

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



Post-earthquake DEM (1m)

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

Main Application types

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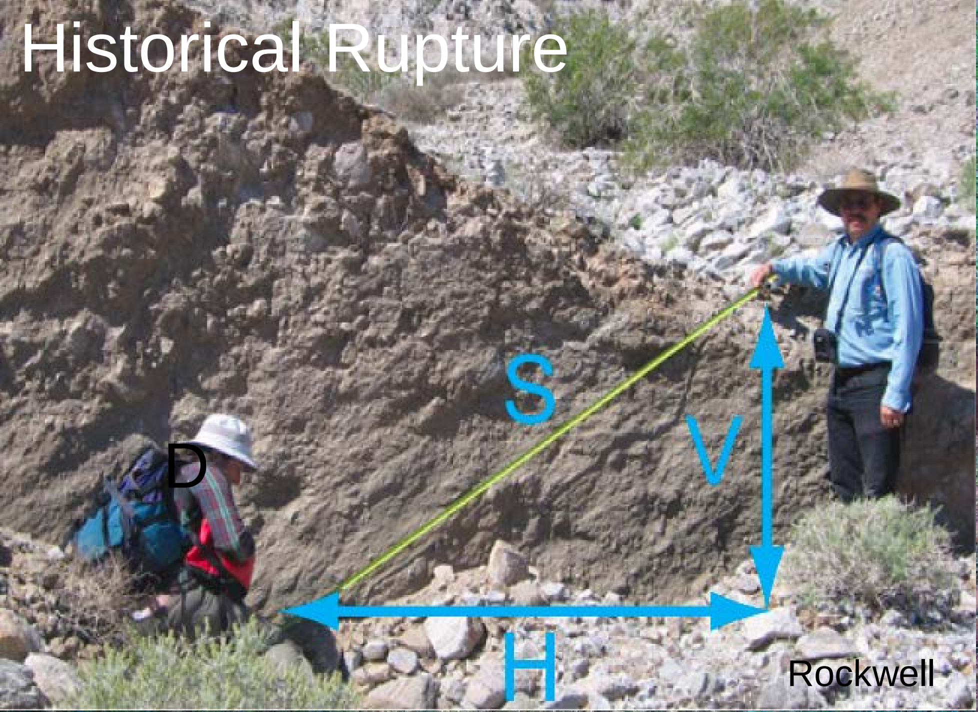
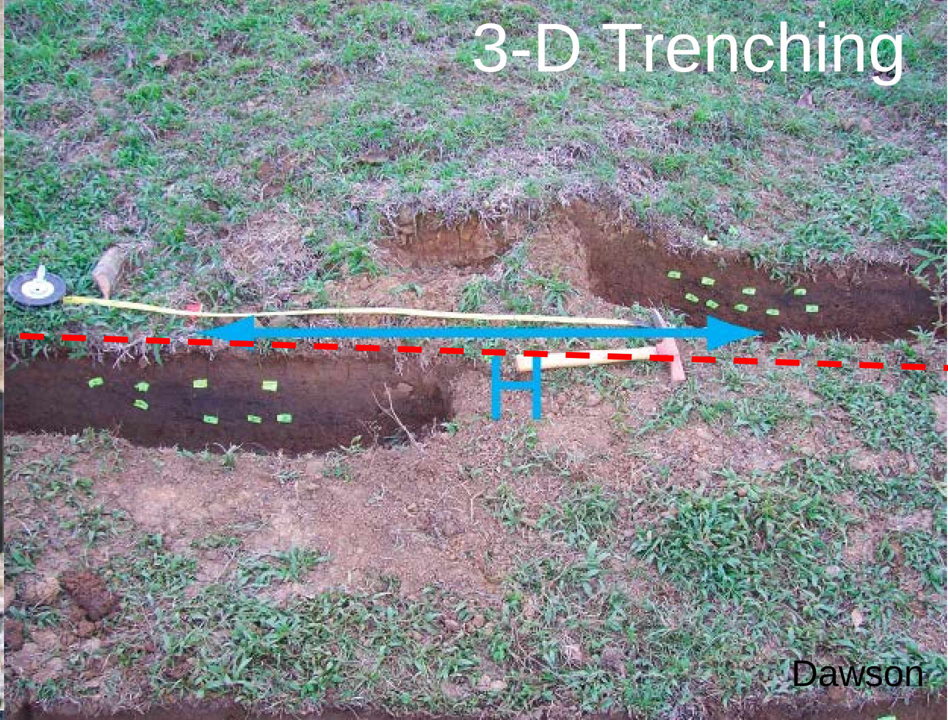
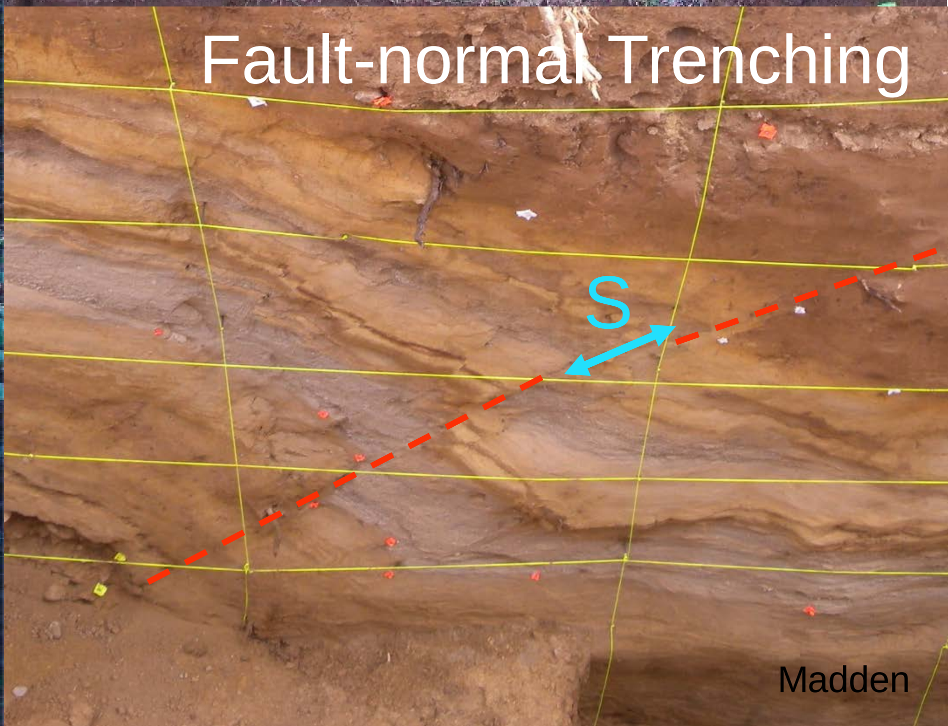

Historical Rupture
S
V
D
H
Rockwell


3-D Trenching
H
Dawson


Geomorphology
H
Salisbury


Fault-normal Trenching
S
Madden

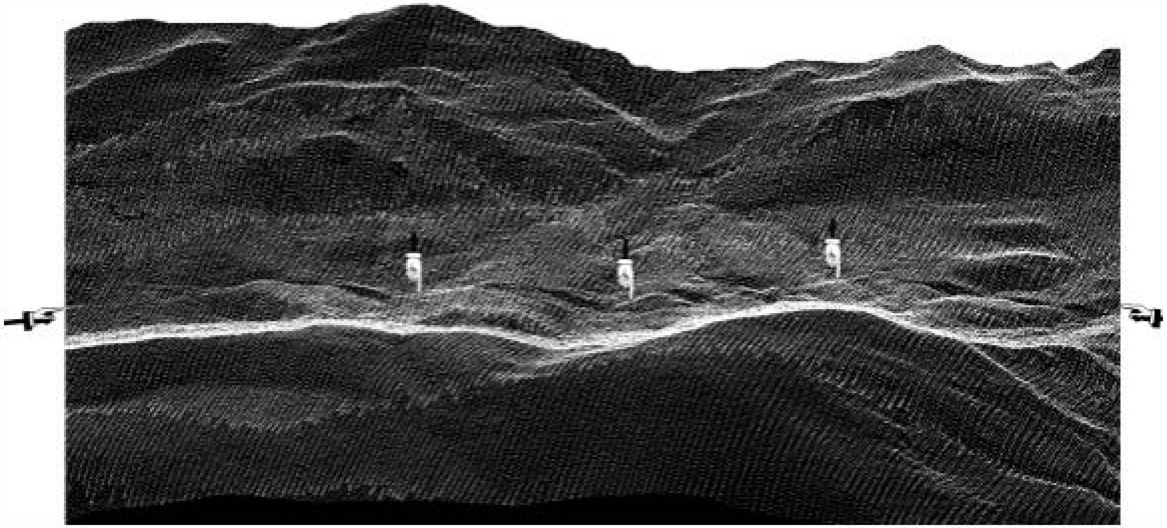


Figure 2. Oblique view of Hector Mine earthquake surface rupture that experienced 3.5–4.5 m of right-lateral displacement. The rupture trace is pointed out by finger icons; the light and dark bands below and above the surface rupture are subparallel, topographic escarpments. Several offset ridges are 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

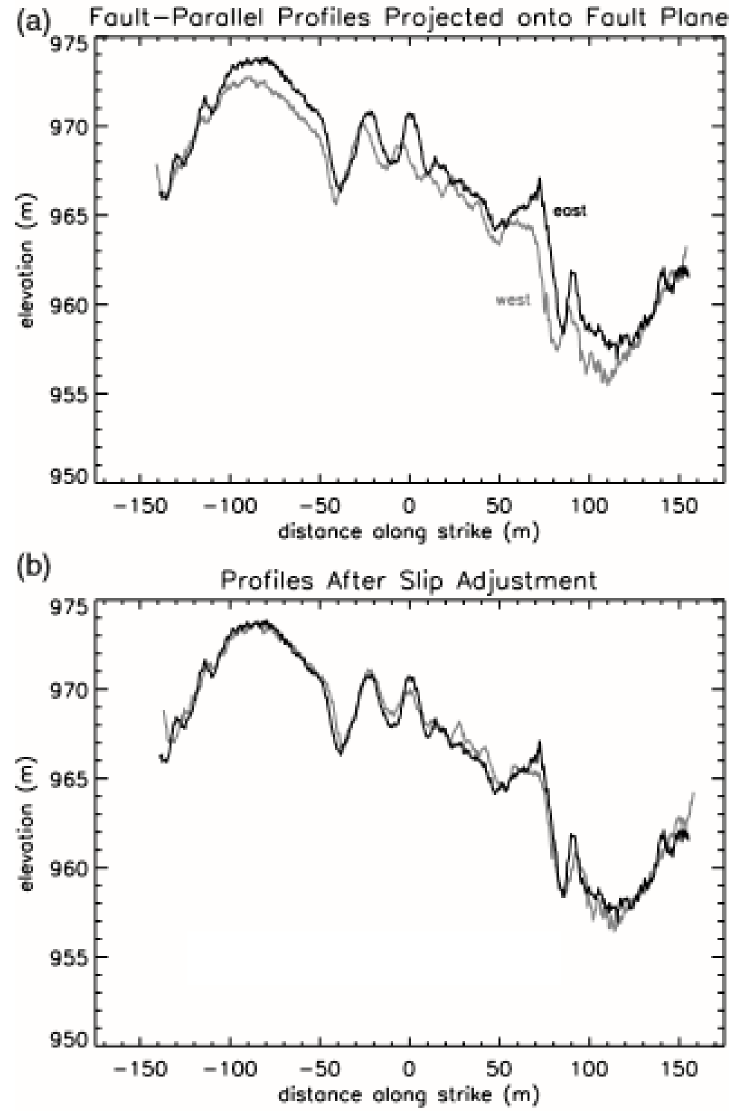
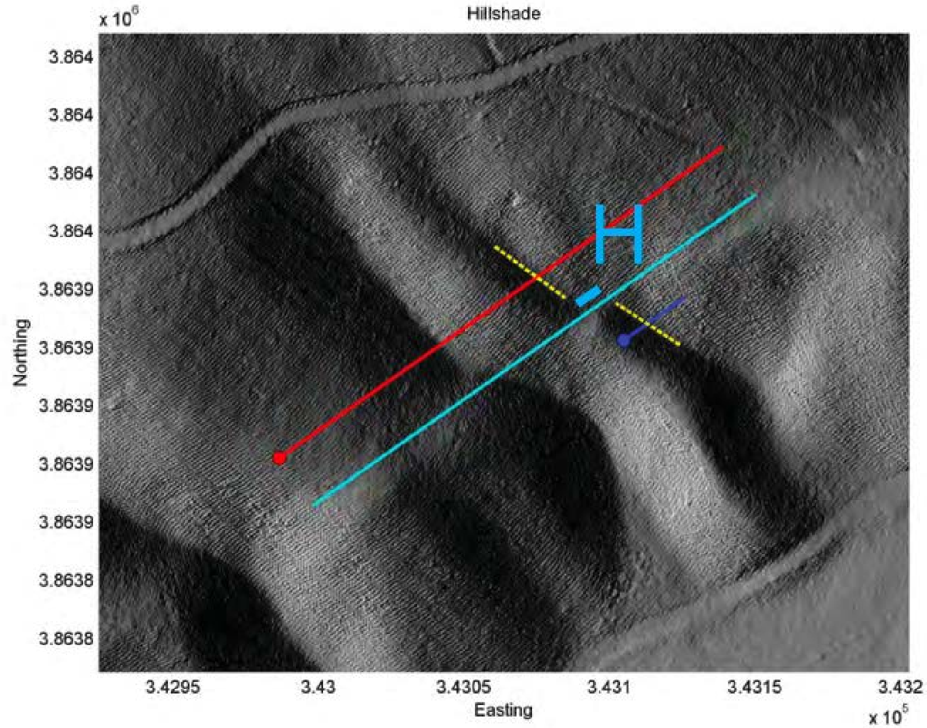
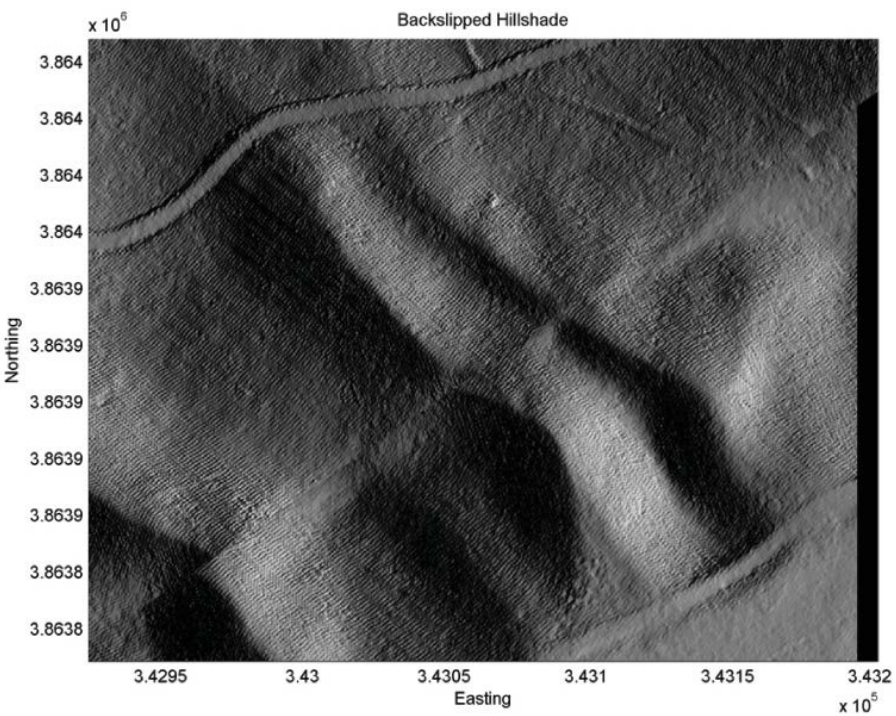
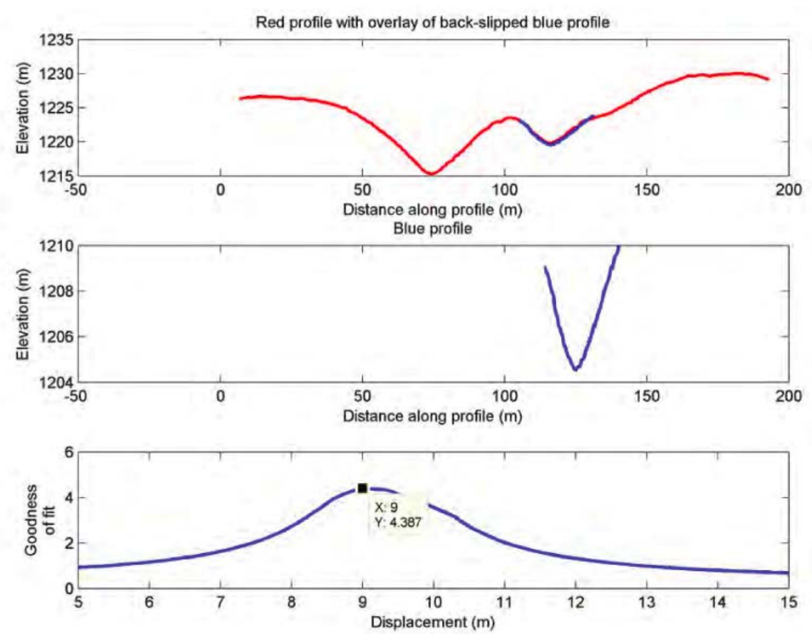


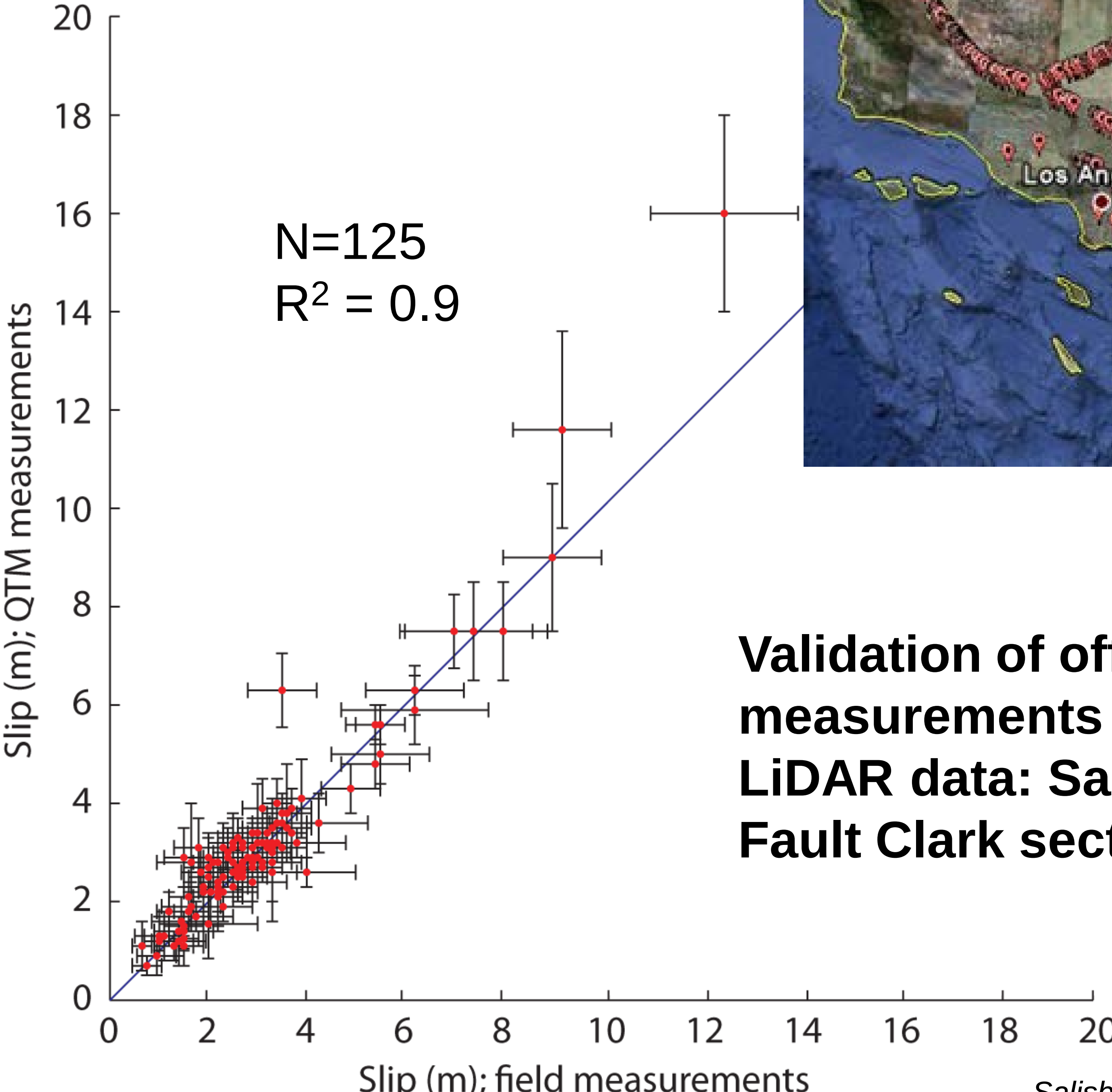
Figure 6. (a) Cross sections through the raw laser data on either side of the surface rupture, along the east and west profiles shown in Figure 4, are shown projected onto the fault plane (a ground-slope correction has already been removed). (b) Comparison of the topographic profiles on either side of 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



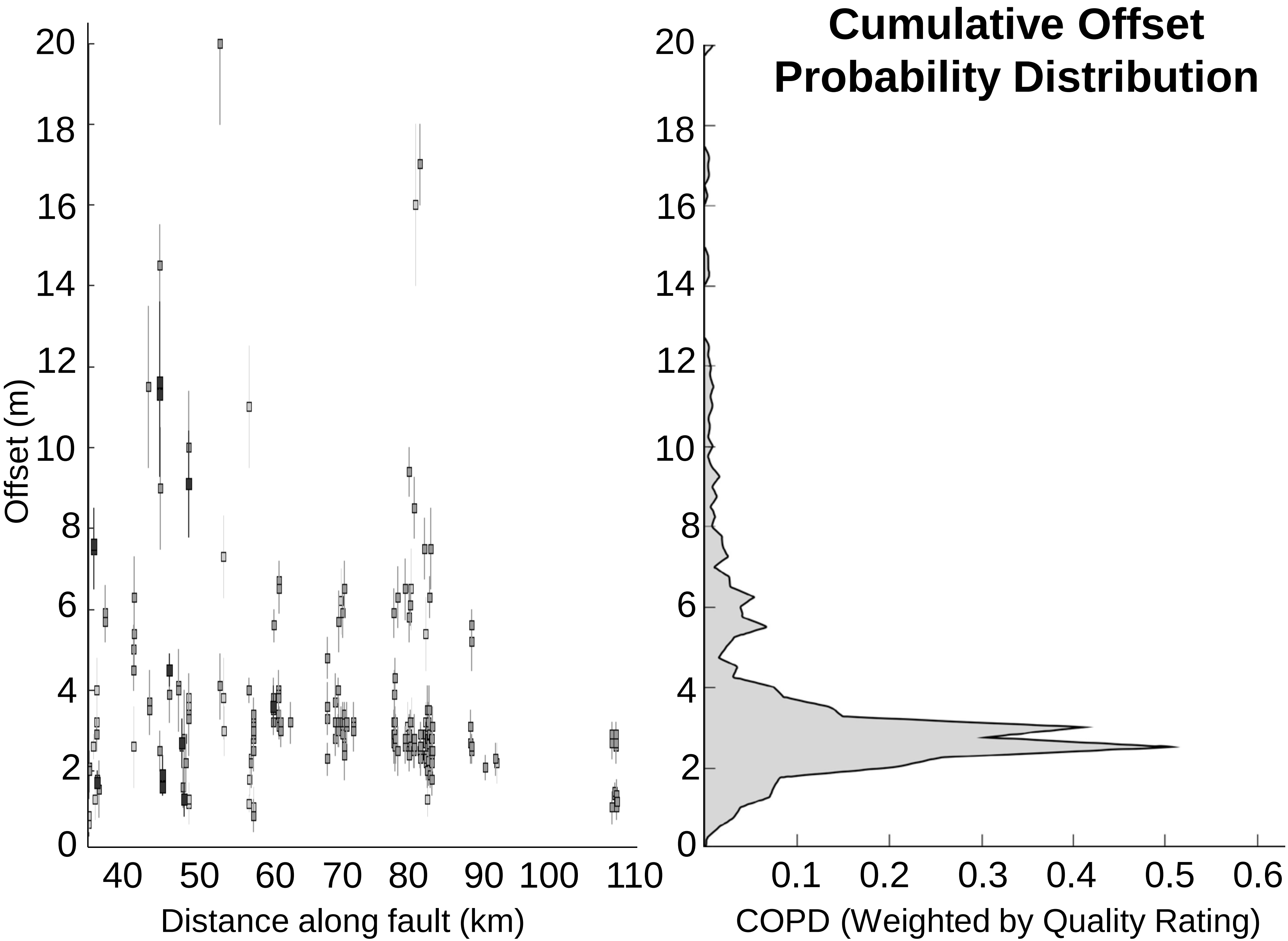




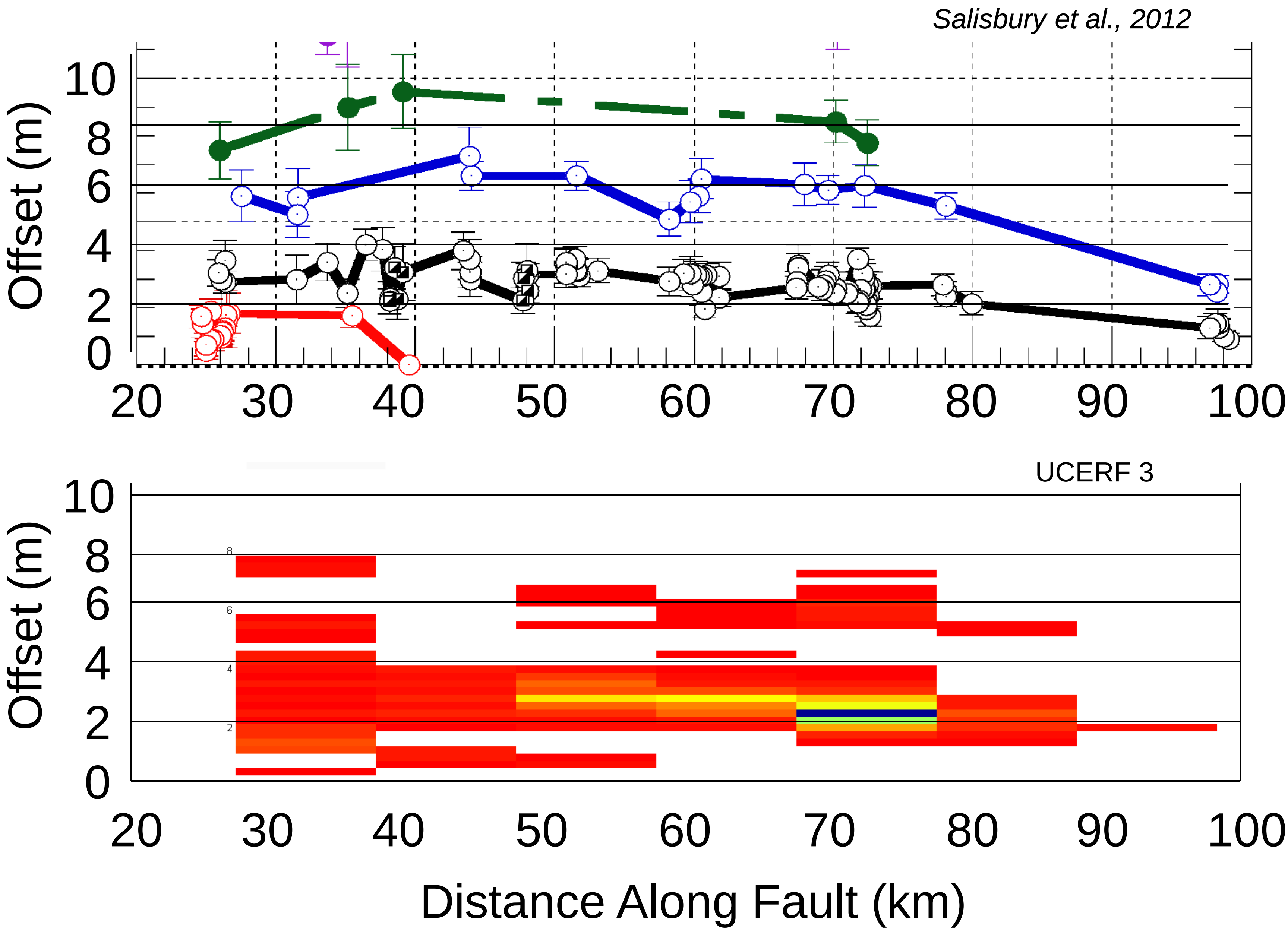


Validation of offset measurements from field and LiDAR data: San Jacinto Fault Clark section

Salisbury et al., 2012



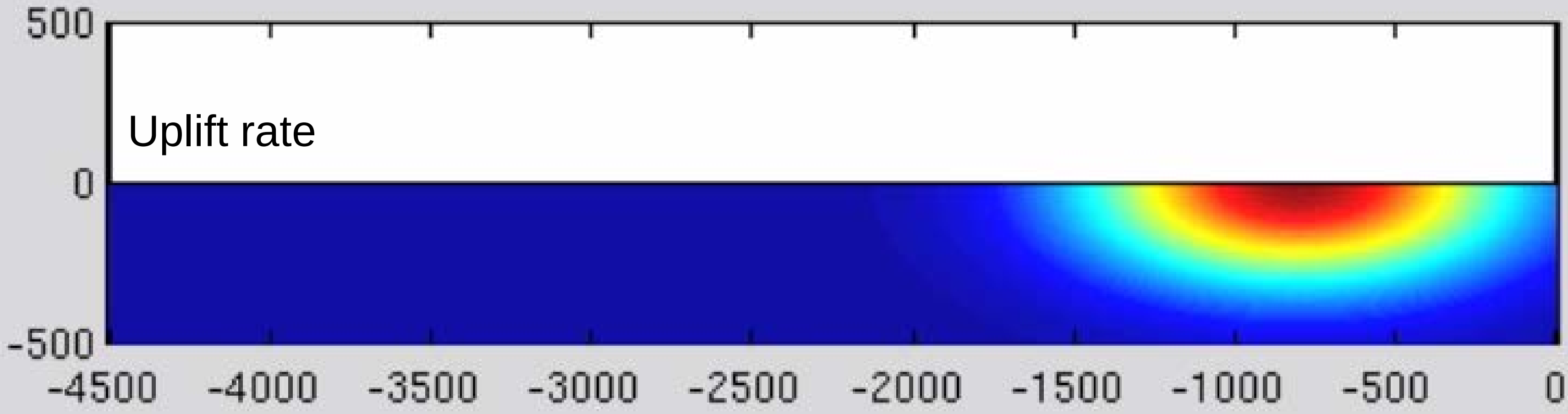
Cumulative Offset
Probability Distribution
Offset (m)
Distance along fault (km)
COPD (Weighted by Quality Rating)
0
2
4
6
8
10
12
14
16
18
20
40
50
60
70
80
90
100
110
0.1
0.2
0.3
0.4
0.5
0.6


Salisbury et al., 2012
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
- Differencing of repeat surveys
- Landscape reconstruction (offsets)
- **Surface process interactions with tectonic or volcanic processes**

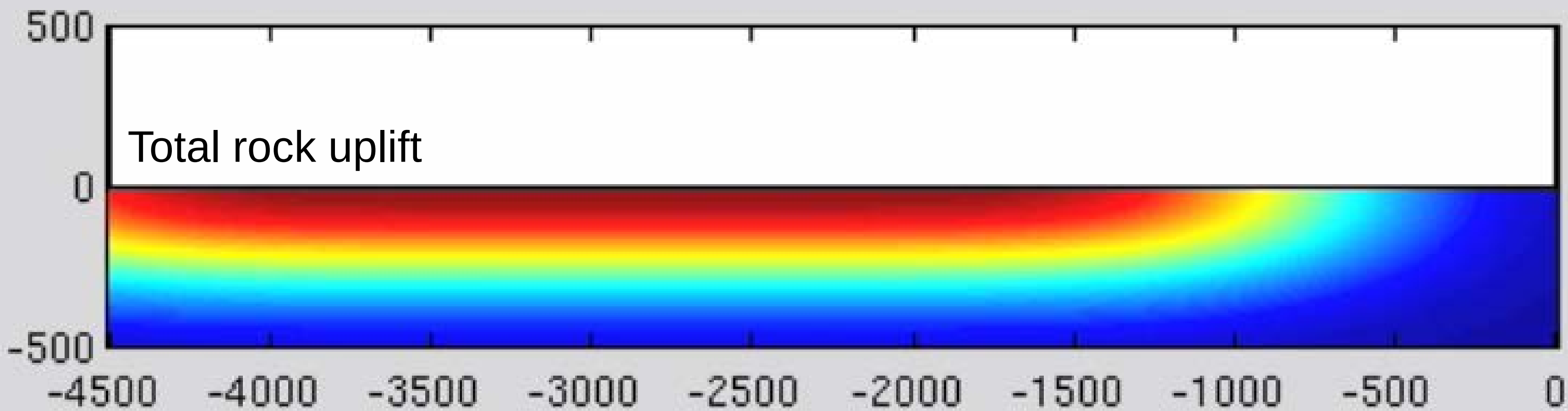
Understanding geomorphic response to uplift



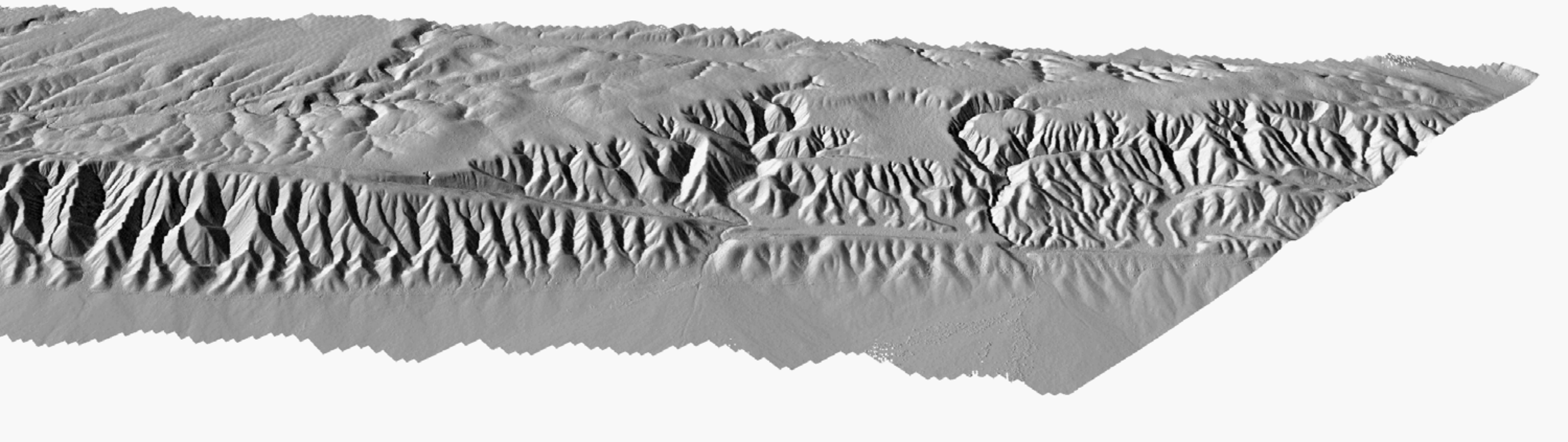
Material moves along fault though relatively stationary uplift zone:

How does landscape respond?

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

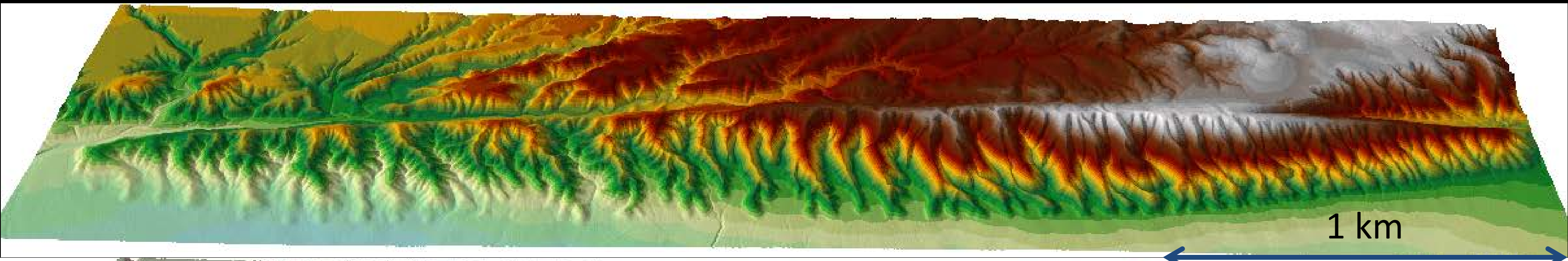


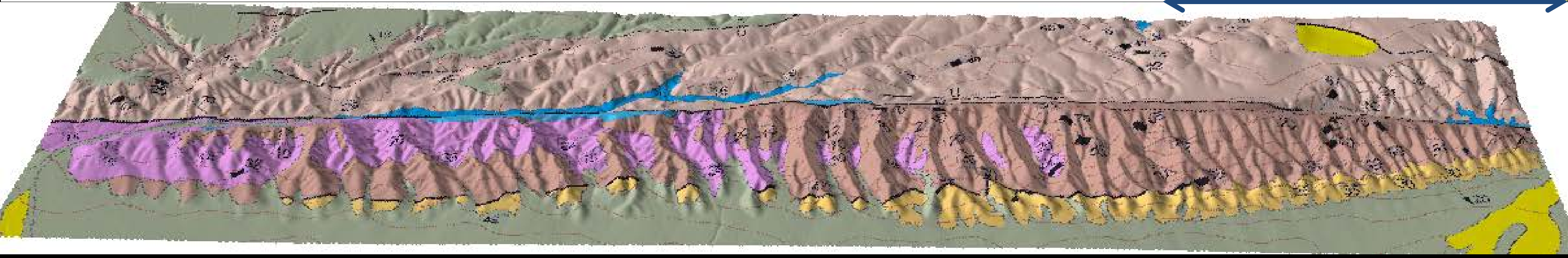
-G. E. Hilley

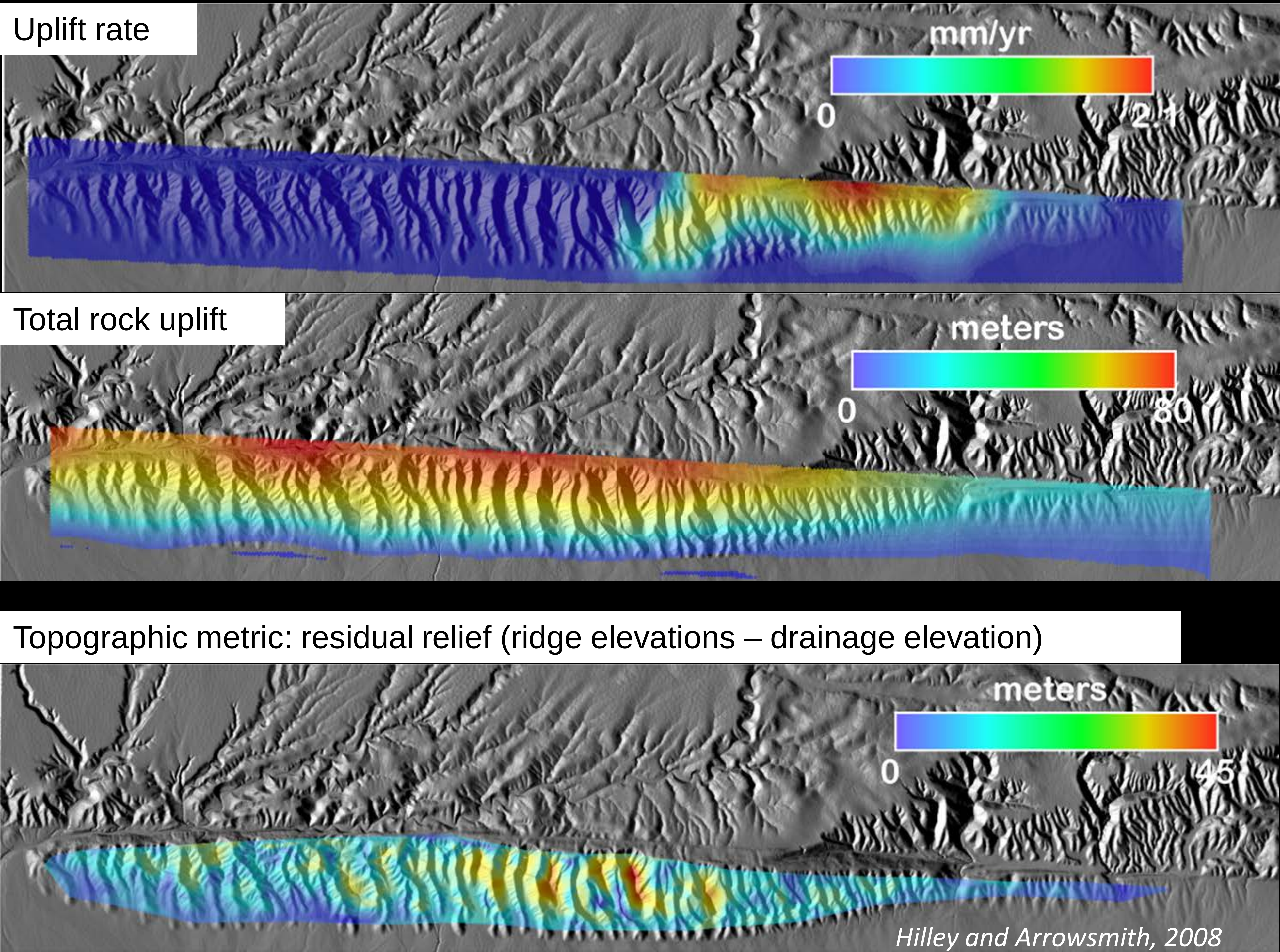


Dragon’s Back Pressure Ridge, Carrizo Plain California

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





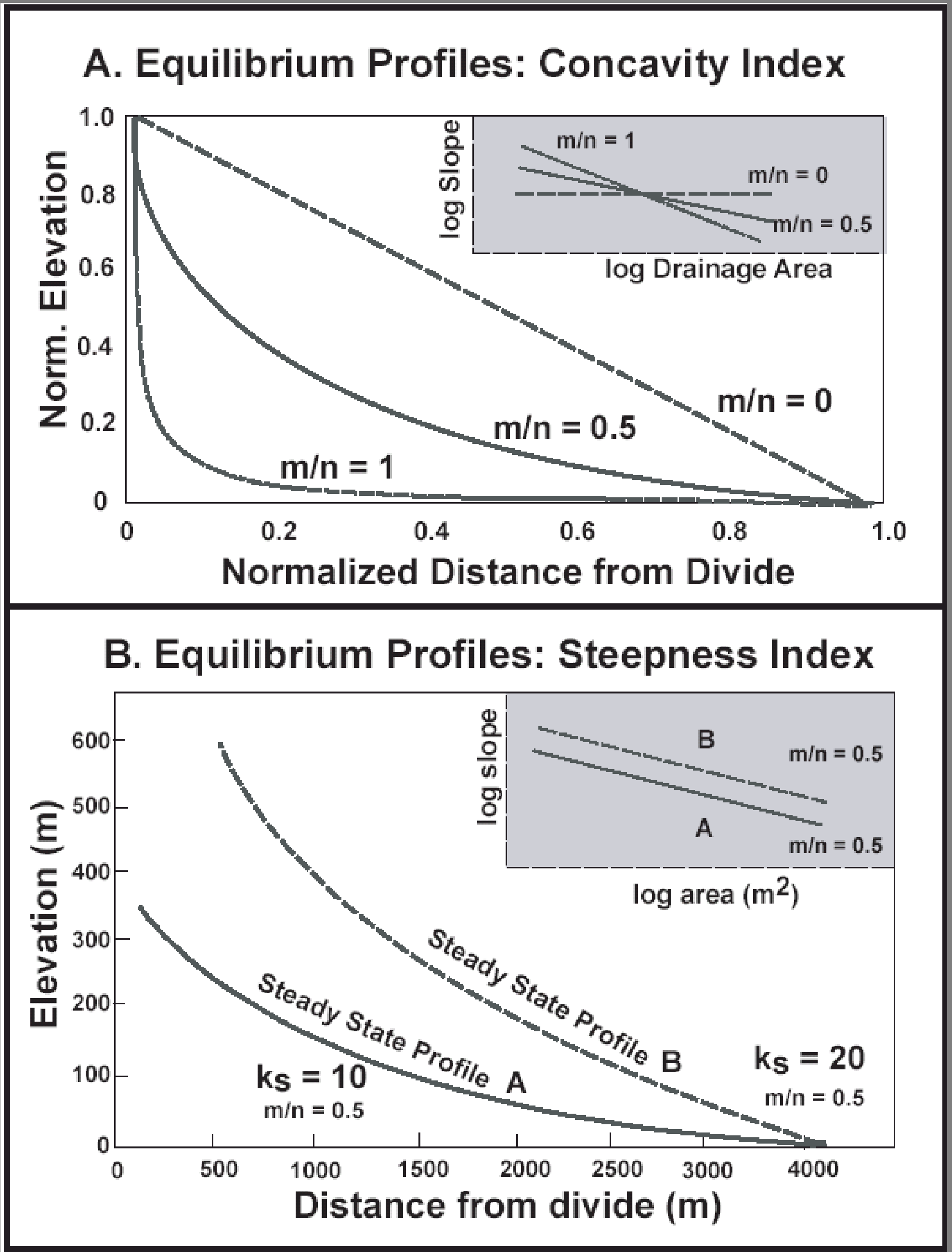

Uplift rate
mm/yr
0
2.1
Total rock uplift
meters
0
80
Topographic metric: residual relief (ridge elevations – drainage elevation)
meters
0
45
Hilley and Arrowsmith, 2008

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

U = Rock Uplift Rate

Concavity (θ) invariant with U

Steepness (Ks) varies with U

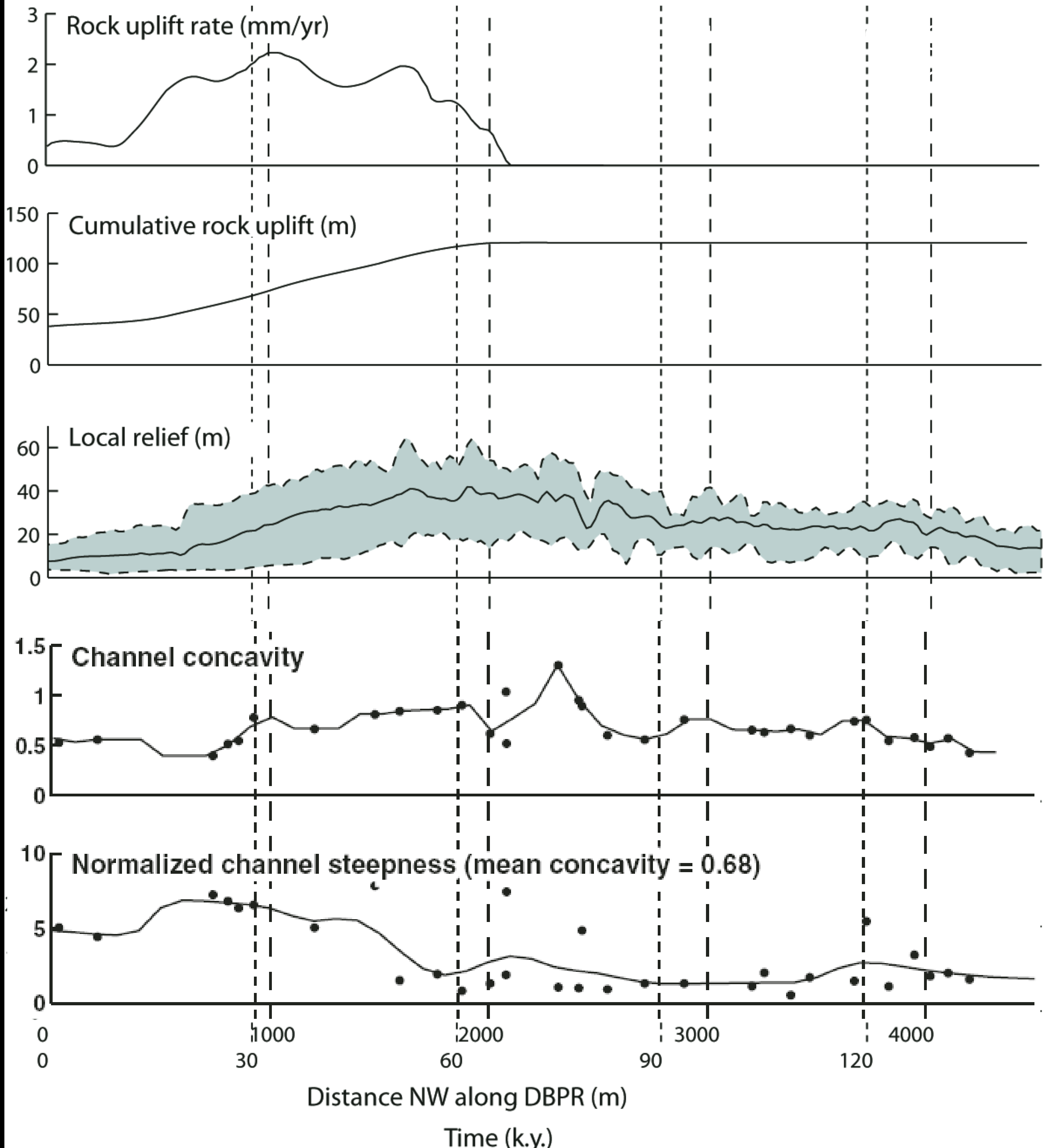


$\theta = m/n$

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

k_s

--K. X Whipple



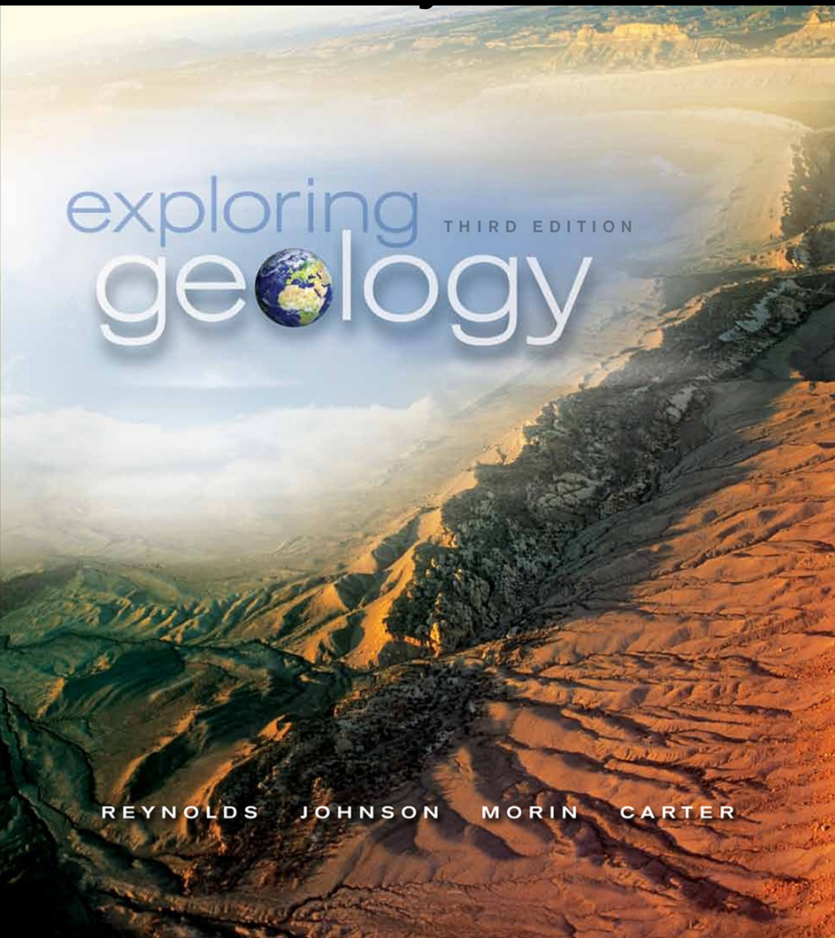
Hilley and Arrowsmith, 2008

Summary

- LiDAR provides dm to cm global accurate measure of the earth’s surface
- Meter scale is critical for 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



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 f
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 characteris
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