Sharpening our view of earth processes with high resolution topography
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.
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

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

A Airborne LiDAR
- onboard GPS and IMU constrain position and orientation of aircraft
- distance between scanner and ground return determined from delay between outgoing pulse and reflected return
- features matched in multiple photographs

B Terrestrial LiDAR
- lines show track of scan across ground
- circles show actual ground return footprints

C Structure from Motion
- motion of camera provides depth information
- scene structure refers to both camera positions and orientations and the topography

Global and regional topography/bathy (10s-100s m/pix)
- Stereo-Photogrammetric Elevation Model (Polar Geospatial Center)

+ASTER

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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;
Length scales $>10^5 \text{m}$ and $<1 \text{ m}$

\[ M = 5.08 + 1.16 \times \log(\text{SRL}) \]

\[ M = 6.93 + 0.82 \times \log(\text{AD}) \]

Wells and Coppersmith, 1994
For differencing, need pre-event data.
“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
Cinder cone slope analysis

USGS NED 10 m DEM

SfM 0.2 m DEM

Topographic slope distributions

Low slope at base

Flank modes

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

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

Vedder and Wallace, 1970 and numerous others
Going beyond pretty pictures: the hillshades are very nice, but...
Characterizing arid region alluvial fan surface roughness with airborne laser swath mapping digital topographic data

Kurt L. Frankel and James F. Dolan

JGR, 2007
Morphologic dating of fault scarps using airborne laser swath mapping (ALSM) data

G. E. Hilley,¹ S. DeLong,² C. Prentice,² K. Blisniuk,³ and JR. Arrowsmith⁴

GRL, 2010
Down the flow

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

Pyle and Elliott, Geosphere, 2006
Main Application types

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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:

SC/EC
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)
Dense 3-D displacements in an area InSAR cannot image

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

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

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Historical Rupture

3-D Trenching

Geomorphology

Fault-normal Trenching
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 pointcloud image. From tens to hundreds of hits per square meter were collected along the primary surface ruptures.

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)
Distance Along Fault (km)

Offset (m)

Salisbury et al., 2012

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Main Application types

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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
U = Rock Uplift Rate

Concavity ($\theta$) invariant with U

Steepness ($K_s$) varies with U

$\theta = \frac{m}{n}$

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

--K. X Whipple

\[ Duvall, Kirby, and Burbank, 2004, JGR-ES \]
Rock uplift and topographic metrics

Substitution of space for time

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

Getting Lidar into introductory textbooks!

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 happen in various settings, including transform plate boundaries and within the interiors of plates.

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 features formed where one block of rock shears past another or where rocks are forced around a bend in the fault.

Before You Leave This Chapter, Be Able To
- Describe or sketch how deformation and metamorphism occur in continental rifts, rifted continental margins, and mid-ocean ridges.