The M7 2016 Kumamoto, Japan, Earthquake: Surface Strain in the Fault Damage Zone and Shallow Fault Slip Revealed with Near-Field Geodetic Imagery

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Motivation & Outline

Upper fault zone behavior: How is slip transmitted to the surface?

Differential topography fills near-fault data gap.

Inelastic failure of fault zone produces distributed deformation.

Fault slip inversion from topography, optical, and InSAR.

Broader impacts: Undergraduate lab; OpenTopography
What is the behavior of the upper fault zone?

Does fault slip propagate through the velocity-strengthening portion of the crust?

**Challenge:** How to measure surface deformation with the fault zone?

**Challenge:** Is the upper crust best represented with an elastic rheology?

‘Business as usual’
What is the behavior of the upper fault zone?

Does fault slip propagate through the velocity-strengthening portion of the crust?

**Challenge:** How to measure surface deformation with the fault zone?

**Challenge:** Is the upper crust best represented with an elastic rheology?

‘No business’
What is the behavior of the upper fault zone?

Does fault slip propagate through the velocity-strengthening portion of the crust?

**Challenge:** How to measure surface deformation with the fault zone?

**Challenge:** Is the upper crust best represented with an elastic rheology?

‘Busy business’
Topographic differencing: Previous work

2010 M7.2 El Mayor-Cucupah Earthquake
Oskin et al. (2012)

The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan
Nissen et al. (2014)
2016 M7.1 Kumamoto, Japan, Earthquake

<table>
<thead>
<tr>
<th></th>
<th>Date</th>
<th>Shot density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre- EQ</td>
<td>15 April, 2016</td>
<td>2.5 pts/m²</td>
</tr>
<tr>
<td>Post- EQ</td>
<td>23 April, 2016</td>
<td>3.5 pts/m²</td>
</tr>
</tbody>
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Scott et al. (2018): JGR; Scott et al. (2019): GRL;
3D coseismic displacement: **Iterative closest point (ICP)**

Windowed subset  3D rigid-body deformation  Uncertainty

Besl and McKay (1992); Geiger et al. (2012); Nissen et al. (2012; 2014); Scott et al. (2018)
3D coseismic deformation

Deformed point cloud = \[
\begin{pmatrix}
1 & -\gamma & \beta \\
\gamma & 1 & -\alpha \\
-\beta & \alpha & 1
\end{pmatrix}
\begin{pmatrix}
\text{Undeformed point cloud}
\end{pmatrix}
+ \begin{pmatrix}
t_x \\
t_y \\
t_z
\end{pmatrix}
\]

Coordinate system

Align pre- and post-earthquake point clouds

Scott et al. (2018)
3D Displacement Fields

Scott et al. (2018)
Displacement uncertainty

Scott et al. (2018)
Surface displacement at increasing aperture

Surface: Field data

Tens of meters depth: Displacement discontinuity

To the depth of the seismogenic zone:
Joint lidar- optical correlation- InSAR slip inversion

Scott et al. (2018)
Surface offset measurements

From Shirahama et al. (2016)
Displacement discontinuity: 10’s m aperture
Coseismic strain

First invariant of 2D strain tensor (area change)

Elastic strain limit:
\[ \varepsilon_{\text{yield}} = \sigma_{\text{yield}} / E \approx 0.5\% \]

Scott et al. (2018)
Joint differential lidar topography- optical correlation- InSAR earthquake source inversion
Distributed slip inversion: Mw 7.09 ↓–0.05 ↑+0.03

Datasets: Topographic differencing, optical correlation, InSAR

Scott et al. 2019
Lidar

Optical

InSAR

Scott et al. 2019
Fault slip constraints

Grand Challenges in Geodesy:
The need to better express data constraints

Scott et al. 2019
Slip Inversion
Regularization

Scott et al. 2019
Compare slip inversions

Topography, optical, InSAR

Optical, InSAR

Scott et al. 2019

Asano & Iwata (2016): Strong motion seismic

Kobayashi et al. (2017): Strong motion seismic, teleseismic, GNSS

Scott et al. 2019
Science Conclusions

We examine surface deformation and coseismic fault slip from differential topography, optical correlation, and InSAR imagery. The inelastic failure of damaged fault zone rocks caused by the high strains produces a distributed deformation signal.

The apparent on-fault slip depletion is likely accommodated as off-fault inelastic deformation.

Future earthquakes will likely be recorded with hybrid datasets. New opportunity to learn about shallow fault slip.

Next: Broader impacts
Students pretend to work for the Utah GS following a hypothetical EQ:

1. Visualize how earthquakes deform landscapes.
2. Relate fault slip, surface displacement, and earthquake magnitude.
3. Interpret quantitative geospatial datasets with uncertainty.
Material includes:
• Pre-laboratory lecture
• Lab handout
• Student video

• Pre- and post-earthquake topographic datasets
• By request to cpscott1@asu.edu:
  • Solutions video
On-demand Topographic differencing

Infrastructure damage during the 2016 M7 Kumamoto earthquake

Vertical difference (m)

3 0 3
**Workflow**
Overlapping data
Identical grids
Raster subtraction
Error threshold

**Challenges**
Legacy data
- Invaluable
- Quality control
Hybrid data
- point cloud and raster
- TLS, SfM, global raster
Cyber-infrastructure
3D differencing:
Coming soon

Scott et al. In Review
Where can I perform differencing?

www.opentopography.org

~40 dataset pairs
Critical Zones
Earthquakes
Volcanic eruptions
Rockfalls
Fluvial Processes
Landslides
Urban growth

Many geomorphic and active tectonic processes
Thank you!

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Optical Correlation-InSAR

![Graph showing the distribution of coseismic slip in a 3D plot with axes for ENE (km), NNN (km), and Depth (km). The color bar indicates the coseismic slip in meters, ranging from 0 to 5.2.](image-url)
Hinagu Fault      Futagawa Fault      Entire Earthquake