

# Geophysical Research Letters

## RESEARCH LETTER

10.1029/2019GL082202

### Key Points:

- We conduct an earthquake slip inversion using differential lidar topography, optical image correlation, and InSAR imagery
- We show how each data set constrains the variable fault slip
- The apparent shallow slip deficit may reflect shallow off-fault deformation

### Supporting Information:

- Supporting Information S1
- Data Set S1
- Data Set S2

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### Citation:






Scott, C., Champenois, J., Klinger, Y., Nissen, E., Maruyama, T., Chiba, T., & Arrowsmith, R. (2019). The 2016 M7 Kumamoto, Japan, earthquake slip field derived from a joint inversion of differential lidar topography, optical correlation, and InSAR surface displacements. *Geophysical Research Letters*, *46*. <https://doi.org/10.1029/2019GL082202>

Received 28 JAN 2019

Accepted 31 MAR 2019

Accepted article online 10 APR 2019

## The 2016 M7 Kumamoto, Japan, Earthquake Slip Field Derived From a Joint Inversion of Differential Lidar Topography, Optical Correlation, and InSAR Surface Displacements

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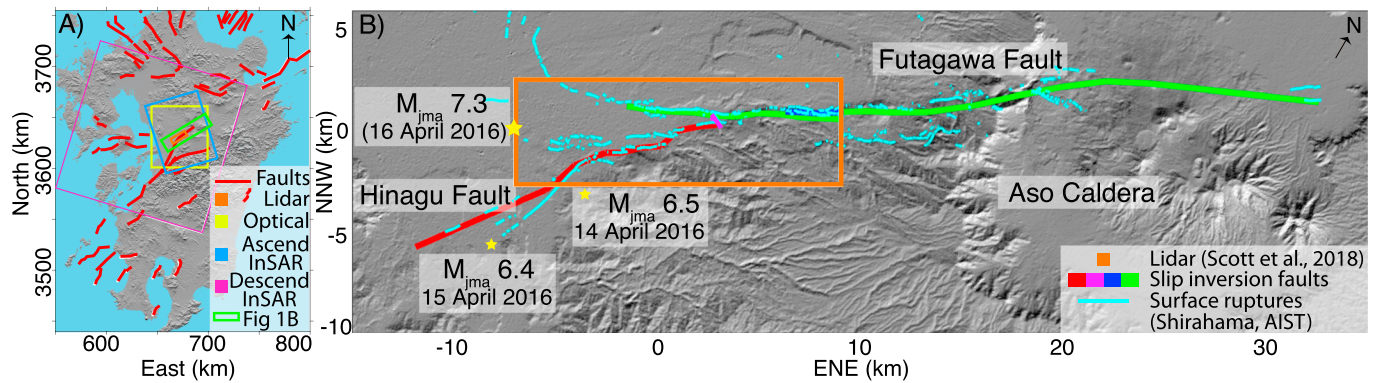
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**Abstract** Observations of surface deformation within 1–2 km of a surface rupture contain invaluable information about the coseismic behavior of the shallow crust. We investigate the oblique strike-slip 2016 M7 Kumamoto, Japan, earthquake, which ruptured the Futagawa-Hinagu Fault. We solve for variable fault slip in an inversion of differential lidar topography, satellite optical image correlation, and Interferometric Synthetic Aperture Radar (InSAR)-derived surface displacements. The near-fault differential lidar pose several challenges. The model fault geometry must follow the surface trace at the sub-kilometer scale. Integration of displacement datasets with different sensitivities to the 3D deformation field and varying spatial distribution permits additional complexity in the inferred slip but introduces ambiguity that requires careful selection of the regularization. We infer a  $M_w 7.09^{+0.03}_{-0.05}$  earthquake. The maximum slip of 6.9 m occurred at 4.5-km depth, suggesting an on-fault slip deficit in the upper several kilometers of the crust that likely reflects distributed and inelastic deformation within the shallow fault zone.

**Plain Language Summary** Coseismic slip inversions quantify fault slip over a fault surface and serve as critical input into research on rupture propagation, earthquake triggering, and seismic hazard. However, coseismic slip distributions are rarely constrained by observations of surface displacement immediately adjacent to the fault rupture. This limits the quality of slip models within the shallowest crust. We solve for the slip field of the 2016 M7 Kumamoto, Japan, earthquake throughout the seismogenic crust using near- and far-field observations from differential lidar topography, satellite optical image correlation, and Interferometric Synthetic Aperture Radar surface displacements. The near-field differential lidar topography is critical for measuring shallow fault slip. We infer a  $M_w 7.09^{+0.03}_{-0.05}$  earthquake and a maximum slip of 6.9 m at 4.5-km depth. This represents a shallow fault slip deficit where slip is greater at depth than at the surface. The missing shallow along-fault slip is accommodated as off-fault and inelastic deformation, presumably along secondary faults and folds in the shallow crust. Future earthquakes are also likely to be measured with different surface displacement data types. Researchers will have a new opportunity to learn about the behavior of the shallow fault zone and will also be presented with technical challenges such as those discussed here.

### 1. Introduction

Recent advances in geodetic imaging have filled a previous near-fault data gap to reveal coseismic and post-seismic surface deformation along faults and in the surrounding fault volume (Brooks et al., 2017; DeLong et al., 2016; Milliner et al., 2015; Nissen et al., 2012, 2014; Oskin et al., 2012; Scott et al., 2018; Vallage et al., 2015). Inferences of both depleted and elevated shallow slip and off-fault deformation along strike and at depth in different earthquakes have raised questions about the strain budget throughout the seismic cycle. The term *shallow-slip deficit* (e.g., Fialko et al., 2005; Simons et al., 2002) refers to a depletion of slip in the upper several kilometers of the crust, although recent work suggests that the slip deficit be an artifact of the data resolution or may not describe the behavior of all earthquakes (e.g., Xu et al., 2016). Ultimately, quantifying the variability of coseismic slip over the fault surface is critical for accurately mapping crustal strain release throughout the seismic cycle and characterizing controls on shallow fault behavior (Gold



**Figure 1.** (a) Map of the Kyushu Island, southwestern Japan, showing active faults (red) and coverage of the four data sets (Universal Transverse Mercator projection). The ascending and descending Interferometric Synthetic Aperture Radar (InSAR) imagery represent range split-band and standard interferometry, respectively. (b) The 2016 M7 Kumamoto earthquake fault map. Thin blue lines show surface ruptures mapped by Shirahama et al. (2016) and the Ministry of Education, Culture, Sports, Science and Technology and Kyushu University (2017). Red, pink, blue, and green lines show the surface traces of the faults used in the coseismic slip inversion. We refer to the entire red fault as the Hinagu Fault. See Figure 2 for the 3D fault structure. Yellow stars are foreshocks and mainshock epicenters estimated by the Japan Meteorological Agency. Figure 1b and all subsequent figures are rotated to an ENE-NNW oriented coordinate system.

et al., 2015; Milliner et al., 2016; Teran et al., 2015; Zinke et al., 2014). Additionally, this information helps refine inferences of slip rate from paleoseismic, geomorphic, and geologic records (Dolan & Haravitch, 2014).

The M7 2016 Kumamoto ruptured the Futagawa-Hinagu Fault Zone on Kyushu Island of southwestern Japan and produced over 2 m of surface slip. Here we present a joint coseismic slip inversion of the Kumamoto earthquake constrained with near-field differential light detection and ranging (lidar) topography, optical image correlation, and Interferometric Synthetic Aperture Radar (InSAR) surface displacements. The near-field differential lidar topography and optical observations constrain the along- and near-fault surface displacements where InSAR imagery commonly lose coherence. We calculate fault slip throughout the seismogenic zone and discuss several challenges posed by the near-fault observations: (1) The model fault geometry must follow the curving surface rupture imaged by differential lidar topography. (2) The three data types measure different components of the 3D deformation field at varying spatial distributions, adding complexity to the earthquake source inversion. We quantify the influence of each data set on the variable fault slip. (3) We discuss approaches for weighting and regularizing the slip inversion. We show an apparent on-fault slip deficit within the upper 2–3 km of the crust. Likely, this observation reflects off-fault and largely inelastic deformation accommodated as distributed strain within the fault volume.

## 2. Tectonic Setting and the Kumamoto Earthquake

The 2016 Kumamoto earthquake sequence ruptured the Futagawa-Hinagu Fault Zone of Kyushu Island (Figure 1), which is situated on the Eurasian plate and overlies the Nankai trough where the Philippine Sea plate subducts. The right-lateral  $M_{ja}$  6.5 ( $M_w$  6.2) and  $M_{ja}$  6.4 ( $M_w$  6.0) foreshocks of 14 and 15 April, respectively, ruptured the northern part of the Hinagu Fault (T. Kobayashi, 2017). The 16 April  $M_{ja}$  7.3 ( $M_w$  7.0) mainshock propagated ENE for ~40 km along the Hinagu and the adjacent NNW dipping Futagawa Fault, with right-lateral and normal (uplift to the southeast) motion (Kubo et al., 2016; Moya et al., 2017; Shirahama et al., 2016). The earthquake ruptured the left-lateral conjugate shear zone and bifurcated into northern and southern ruptures that accommodate dominantly right-lateral and vertical motion (Figure 1b: Bi), respectively (Shirahama et al., 2016). Aso Caldera is likely responsible for terminating the rupture (Yagi et al., 2016). The earthquake caused intense ground shaking and damage throughout central Kyushu and killed over 100 people.

Multiple research groups produced coseismic slip models using strong motion (Asano & Iwata, 2016; Uchide et al., 2016), teleseismic (Yagi et al., 2016), long-period surface waves, Global Navigation Satellite System, InSAR (Fukahata & Hashimoto, 2016), radar pixel tracking data sets (Himematsu & Furuya, 2016), or a combination of multiple data sets (Hao et al., 2017; Jiang et al., 2017; T. Kobayashi, 2017; Zhang et al., 2018). The

fault geometry varies between the slip models. The Hinagu and Futagawa Faults dip 60–80° N and 60–87° NNW, respectively, although in most models the Hinagu Fault is the steeper of the two. Inferred magnitudes generally vary from  $M_w$  7.0 to 7.1, and the maximum fault slip varies from 5 to more than 6 m.

### 3. Data and Methods

#### 3.1. Data

##### 3.1.1. Differential Topography

The first lidar data set (Chiba, 2018a) was acquired on 15 April 2016 following the foreshock activity, and the second data set was acquired on 23 April 2016 (Chiba, 2018b). The lidar point clouds have shot densities of 2.5 and 3.5 points/m<sup>2</sup>, respectively. Scott et al. (2018) calculate 50-m resolution surface displacements from pre-earthquake and post-earthquake lidar topography using a windowed implementation of the Iterative Closest Point algorithm (ICP; Besl & McKay, 1992; Chen & Medioni, 1992) as shown in Figure 2c. We use these displacements as input to the slip inversion.

##### 3.1.2. Optical Correlation

We measure horizontal displacements by correlating 10-m-resolution optical imagery collected by the Sentinel-2 satellite on 3 March 2016 and 16 February 2017 (Figure 2e) and processed using the open-source software package MicMac (Rosu et al., 2015; Rupnik et al., 2016). Cloud cover prevents us from using imagery that more closely brackets the earthquake.

There are two primary sources of noise in the optical data. First, image-parallel stripes are introduced by the sensor from a push-broom effect (e.g., Barnhart et al., 2014; Stumpf et al., 2018). We mitigate the impact of this source of noise by estimating its spatial characteristics in an area unaffected by the earthquake (Klinger et al., 2018). We apply the estimated correction to the full image. A second noise source reflects the different processing levels of imagery acquired at different times by the European Space Agency.

##### 3.1.3. InSAR

Jiang et al. (2017) measure line-of-sight surface displacements using C-band (5.6-cm wavelength) Sentinel-1 A/B satellite Terrain Observation by Progressive Scans (TOPS) data. They exploit the large range bandwidth of the TOPS data and use split-band interferometry to produce displacements that remain relatively coherent near the fault. We use the published displacements produced using range split-band interferometry and standard interferometry from ascending track 156 (Figure 2f) and descending track 163 (Figure 2g), respectively.

##### 3.1.4. Downsampling

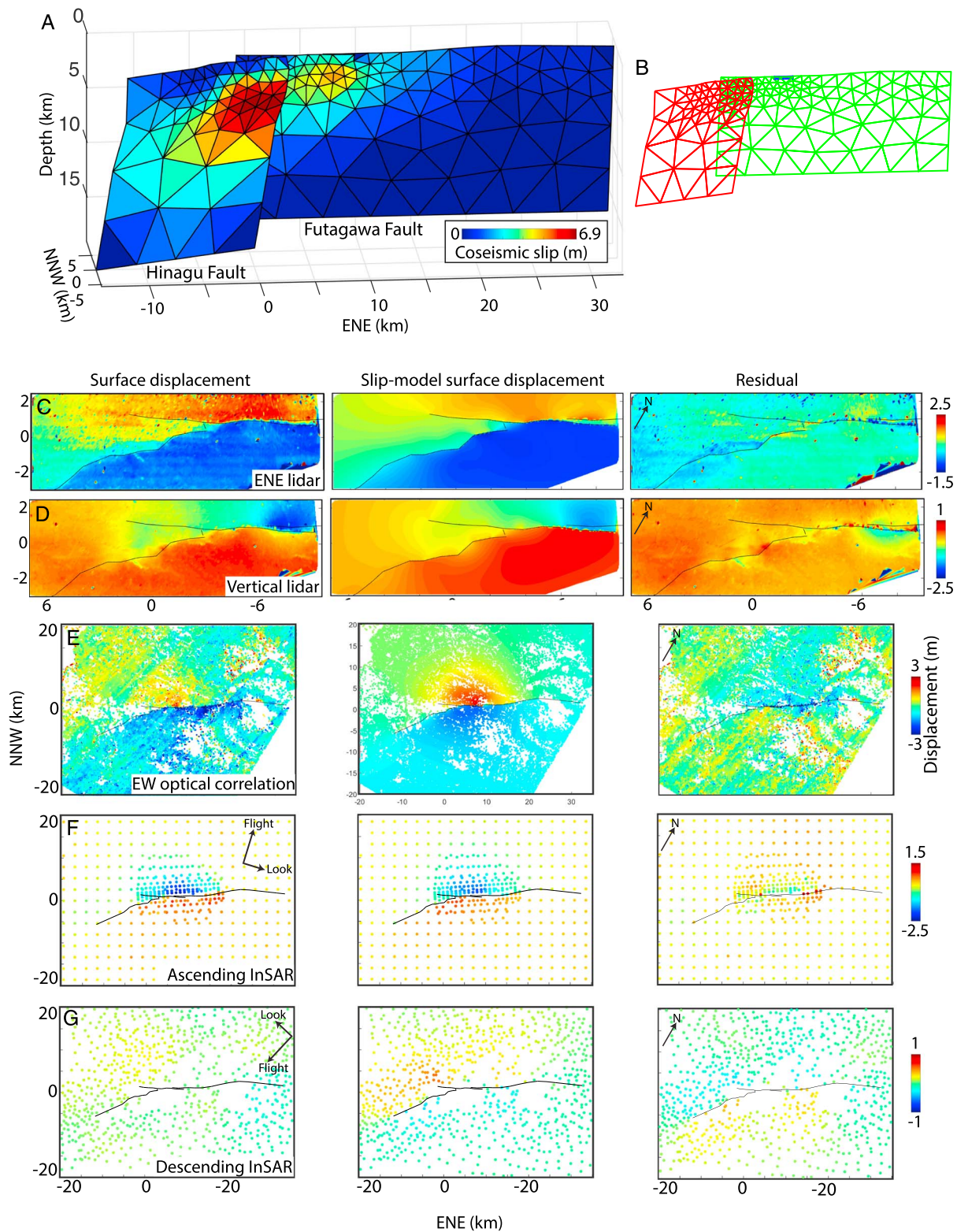
An earthquake slip inversion with the full set of  $10^5$ – $10^6$  lidar and optical surface displacement data points is computationally infeasible. We use the triangular-based fault resolution algorithm developed by Lohman and Simons (2005) and McGuire et al. (2015) to downsample the lidar and optical data sets. This algorithm performs less spatial averaging near the fault to retain the high near-field information from both data sets. Table S2 shows the number data points after downsampling, and Figures S1–S2 show the slip inversion results with the downsampled data. The InSAR imagery from Jiang et al. (2017) is already downsampled to a suitable resolution.

##### 3.1.5. Preseismic and Postseismic Displacements

The datasets span different portions of the preseismic and postseismic time periods and likely record different amounts of deformation before and after the mainshock. Although we do not make any correction for the noncoseismic deformation, we consider the magnitude of deformation produced by the foreshock and postseismic activity when comparing the slip inversion fit to the different data sets. The differential lidar topography is the only data set that does not span either  $\geq M_w$  6 foreshocks. The  $M_w$  6.2 14 April foreshock (Figure 1b) produced  $\sim 1.2$  m of slip at its 12-km-deep epicenter and  $\sim 1$  m at the surface (Asano & Iwata, 2016). The postevent lidar and InSAR imagery were acquired within 1 week of the mainshock, yet the postevent optical imagery was acquired in February 2017. GPS data show displacements of  $\sim 10$  cm directly above the ruptured fault and far-field displacements of  $\sim 5$ – $15$  cm in the first 91 days following the mainshock (Moore et al., 2017).

#### 3.2. Fault Geometry

Typically, the fault geometry of  $>M7$  earthquakes used in earthquake source inversions consists of multiple rectangular fault segments that each have a constant strike and dip (e.g., Barnhart et al., 2014; Huang et al.,



**Figure 2.** (a) Variable fault slip for the lidar-optical-Interferometric Synthetic Aperture Radar (InSAR) inversion. (b) Fault geometry frame with colors corresponding to fault segments in Figure 1b. Subfaults are the individual triangles. Measured (first column) surface displacements, (second column) surface displacements predicted from the preferred coseismic slip inversion, and (third column) residual displacements for the (c) ENE differential lidar topography, (d) vertical differential lidar topography, (e) E-W optical correlation, (f) ascending InSAR, and (g) descending InSAR.

2017; Marchandon et al., 2018; Wei et al., 2011). The use of a curving fault is rare (Wang et al., 2013). The slip inversion for the Kumamoto earthquake requires a kinking surface trace due to the complex fault geometry revealed by the differential lidar topography (Figure 1). We damp the kinking at depth, so that the fault becomes increasingly planar at depth where local complexities in the fault geometry are poorly constrained (Figure 2b). Because data resolution of slip decreases with depth (Motagh et al., 2006; Simons et al., 2002), we increase the area of the subfaults from less than 1 km<sup>2</sup> near the surface to 15 km<sup>2</sup> at 20-km depth using Barnhart and Lohman's (2010) approach. The Futagawa and Hinagu Faults dip 65° and 72°, respectively, consistent with foreshock and aftershock locations published slip models (e.g., Asano & Iwata, 2016), and surface fault exposures (Shirahama et al., 2016). Faults extend to a maximum depth of 20 km. Where the Futagawa Fault steps to the left at the eastern extent of the lidar coverage, the fault geometry is discontinuous at the surface yet remains connected from 1-km depth to the downdip extent of the fault.

### 3.3. Slip Inversion and Regularization

We conduct two sets of joint inversions for variable slip using surface displacements derived from combined (1) lidar-optical-InSAR and (2) optical-InSAR imagery. Here we outline our approach for the joint lidar-optical-InSAR slip inversion. The approach for the optical-InSAR slip inversion (Figures S3– S4) is identical, except we omit the lidar data. We consider the forward fault slip problem

$$\mathbf{G}m = d \quad (1)$$

where  $\mathbf{G}$  is the set of Green's functions that relate fault slip along triangular dislocations ( $m$ ) embedded in an elastic isotropic half-space (Meade, 2007) to surface displacements ( $d$ ). The InSAR phase delays and optical displacements are observed relative to an arbitrary zero level due to satellite orbital errors, resulting in long-wavelength errors in the measured displacement fields (e.g., Fattahi & Amelung, 2014; Hanssen, 2001). To account for these errors, we add terms to  $\mathbf{G}$  that remove a bilinear ramp (e.g., Bekaert et al., 2016) from each of the optical and two InSAR data sets. We do not add equivalent terms for the lidar data set, because the two lidar surveys are tied to the same external reference frame through GPS. We assume a Poisson's ratio of 0.25 and a shear modulus of  $3.0 \times 10^{11}$  dyne/cm<sup>2</sup>.

We apply several constraints to the slip inversion. (1) We select a relative weighting between each of the three data types so that each data type has a similar constraint on the inferred slip distribution (Table S2). (2) The rake varies, but we add positivity constraints to force right-lateral and normal dip-slip motion. (3) We apply Tikhonov Laplacian regularization along each fault.

The preferred slip distribution minimizes the norm (Aster et al., 2013; Menke, 1984):

$$\min \left\| \begin{bmatrix} \mathbf{G}_w \\ \lambda \mathbf{L} \end{bmatrix} m - \begin{bmatrix} d_w \\ 0 \end{bmatrix} \right\| \quad (2)$$

where  $\mathbf{L}$  is regularization matrix and  $\lambda$  is the regularization parameter. The optimal  $\lambda$  lies at the L-curve corner produced by solving the slip inversion with different regularization parameters (Harris & Segall, 1987). Our quoted uncertainty of the earthquake magnitude reflects the range of magnitudes associated with slip models that lie within the broad L-curve corner, shown by the black uncertainty curve.

The generalized inverse is

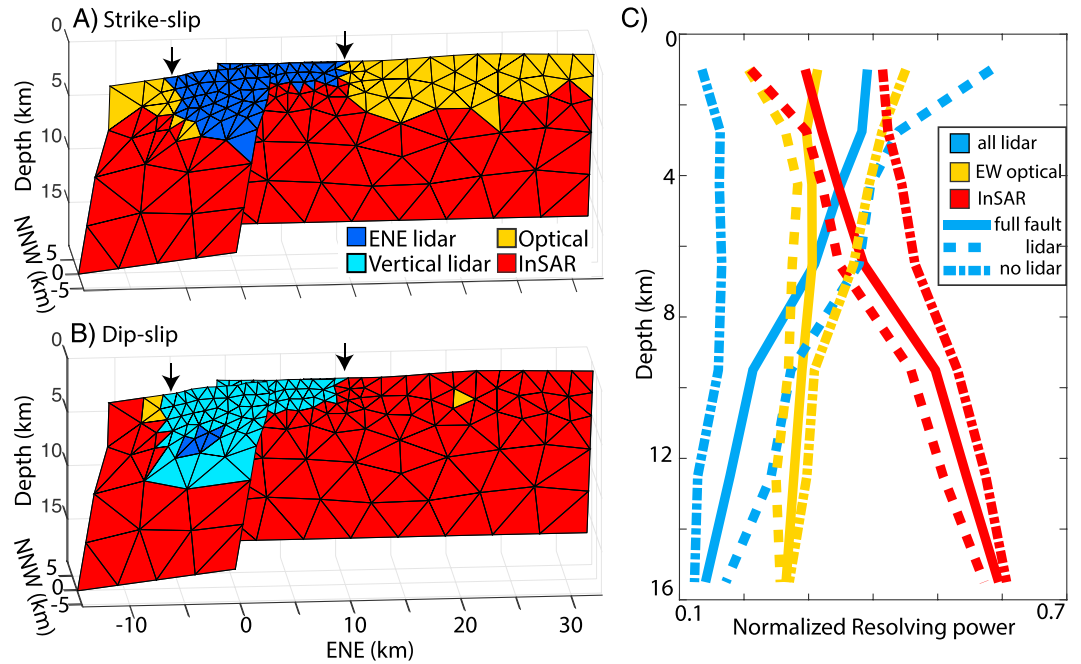
$$\mathbf{G}^{-g} = \left( \begin{bmatrix} \mathbf{G}_w \\ \lambda \mathbf{L} \end{bmatrix}^T \begin{bmatrix} \mathbf{G}_w \\ \lambda \mathbf{L} \end{bmatrix} \right)^{-1} \mathbf{G}_w^T \quad (3)$$

The slip inversion is solved by

$$m = \mathbf{G}^{-g} d \quad (4)$$

### 3.4. Data Set Resolution for Variable Fault Slip

When data sets with varying sensitivity to the 3-D surface deformation field and spatial distributions are combined in a joint slip inversion, knowledge about how each data set constrains the variable slip field



**Figure 3.** Data constraints on the lidar-optical- Interferometric Synthetic Aperture Radar (InSAR) variable slip inversion. The dataset with the highest resolving power is shown for (a) strike-slip and (b) dip-slip motion. Black arrows indicate the spatial extent of the differential lidar. (c) Depth versus the normalized resolving power for the three data types along the entire fault (solid lines), the fault segment within the lidar footprint (dashed lines), and the fault segment outside of the lidar coverage (dotted lines).

serves as a critical constraint on the slip inversion quality. We extend Barnhart and Lohman's (2010) technique and calculate how each data set resolves the slip field. The resolving power  $R$  at subfault  $i$  from dataset  $j$  is the norm of the terms in  $G^{-g}$  whose row corresponds to fault patch  $i$  and columns to dataset  $j$ :

$$R_{\text{patch } i, \text{ data set } j} = |G^{-g}(\text{patch}_i, d_j)| \quad (5)$$

Due to the nonlinear positivity constraints, the slip inversion is nonlinear. Therefore,  $R$  is only an approximate measure of the data resolution. Figures 3a and 3b show the data set with the greatest  $R$  for each subfault. We calculate the resolving power at specific depths ( $R_{\text{depth } i, \text{ data set } j}$ ) by taking the norm of  $R$  for the set of subfaults located 1.5 km above or below depth  $i$  (Figure 3c):

$$R_{\text{depth } i, \text{ data set } j} = \sqrt{\sum_{k=1}^N R_{\text{patch } k, \text{ data set } j}^2}. \quad (6)$$

At each depth range, we normalize the combined resolving power of all data sets to unity.

## 4. Results and Discussion

### 4.1. Joint Earthquake Source Inversion

The lidar-optical-InSAR slip inversion (Figure 2a) calculates a  $M_w$   $7.09_{-0.05}^{+0.03}$  earthquake given the assumed elastic half-space parameters (Figure 4a) and uncertainty reflecting the regularization choice. The earthquake ruptured a 40-km along-strike length and a 20-km width. It produced a maximum slip of 6.9 m at 4.5-km depth along the eastern section of the Hinagu Fault. Slip is lower in magnitude and less concentrated along the Futagawa Fault relative to the Hinagu Fault. Slip decreases rapidly past Aso Caldera.

The lidar-optical-InSAR inversion reproduces the first-order displacement fields of the three data types. The largest differential lidar topography residuals (Figures 2c and 2d) occur near the fault and reflect a combination of an oversimplified fault geometry, off-fault deformation, and the elastic rheology assumption. The E-W optical data appear to show a narrower deformation signal than is produced by the slip inversion

(Figure 2e). In contrast, the ascending InSAR imagery (Figure 2f) record a broader signal than is captured by the slip model. Postseismic deformation cannot explain the differences in model fit between the two data types, because the InSAR data were acquired 10 months prior to the optical data. Because the residual optical deformation signal (Figure 2e) contains N-NNE oriented stripes immediately adjacent to the fault, we propose that the optical data misfit reflects the satellite's push-broom error.

For the optical-InSAR slip inversion, we infer a  $M_w 7.10^{+0.02}_{-0.02}$ . The earthquake produces at maximum slip of 5.2 m at 1.3-km depth. There is a similar quality of fit to the surface displacements for both the lidar-optical-InSAR and optical-InSAR earthquake source inversions.

The lidar-optical-InSAR inversion places the maximum slip and 61% of the total moment release on the Hinagu Fault, while the optical-InSAR places the maximum slip on the Futagawa Fault and equal moment release on both faults. As shown in Figure 4c, the fault that hosts the maximum moment release depends on the regularization. For the lidar-optical-InSAR inversion, the Hinagu Fault hosts the greatest moment release at the L-curve corner. For both inversions, the moment release shifts toward the Futagawa Fault with increasing regularization. For all regularization values, the lidar-optical-InSAR inversion resolves a greater maximum slip than does the lidar-optical inversion, yet both inversions result in similar earthquake moments for the preferred slip model.

We compare our two slip fields with slip fields constrained from a strong-motion seismic data set (Asano & Iwata, 2016) and from strong-motion seismic, teleseismic, and geodetic (H. Kobayashi et al., 2017) data sets in Figures 4g–4j. The lidar-optical-InSAR and optical-InSAR slip models produce slip that is shallow (i.e., closer to the fault trace) and localized to either the Hinagu Fault or the central portion of the Futagawa Fault relative to the slip models from Asano and Iwata (2016) and H. Kobayashi et al. (2017). The difference in slip concentration likely reflects the broader spatial distribution of the seismic data used to constrain the latter two slip fields.

#### 4.2. Data Constraints on Fault Slip as a Function of Depth

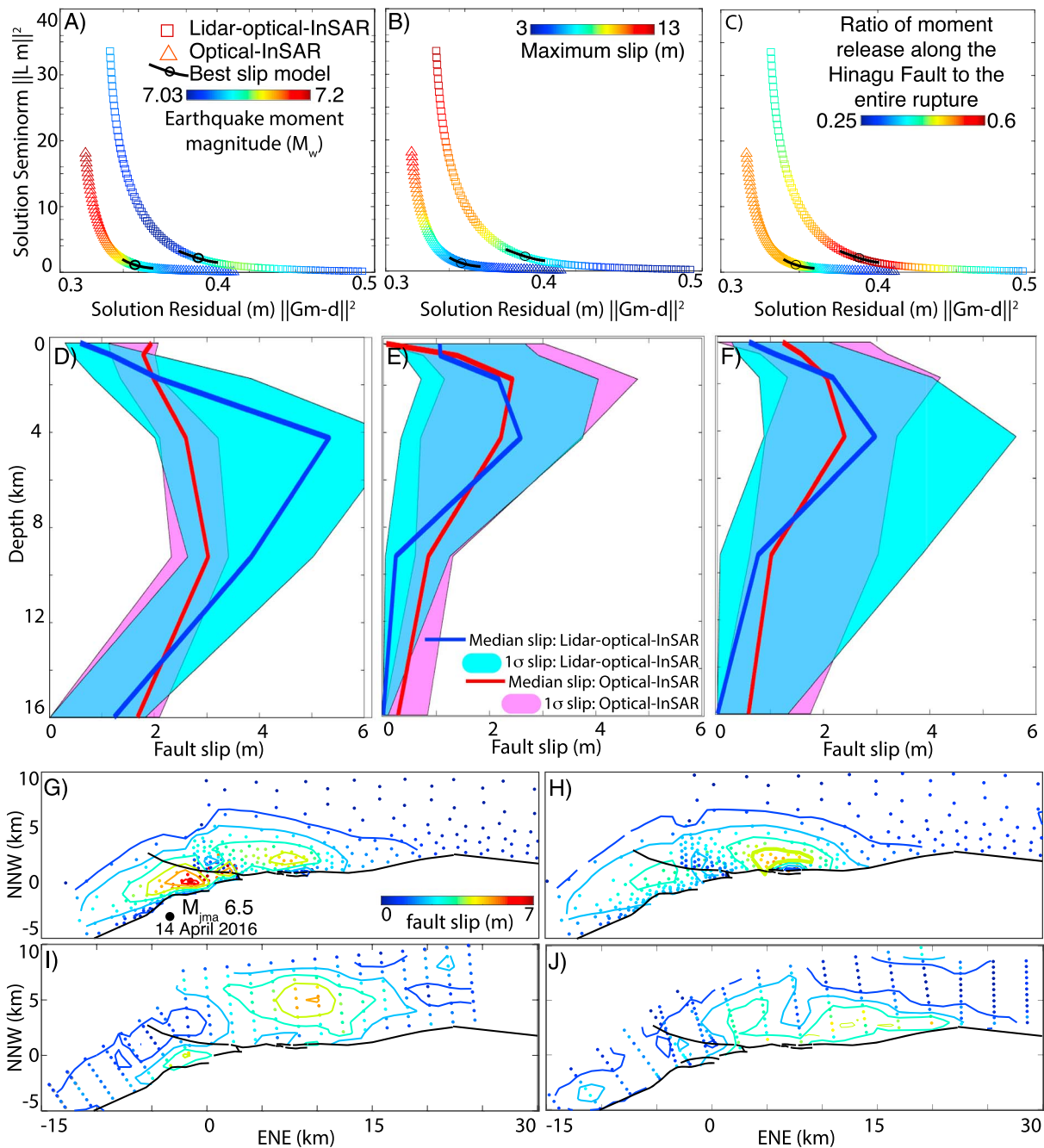
The differential lidar topography constrain shallow strike-slip and dip-slip motion within the lidar footprint denoted by the black arrows in Figures 3a and 3b. The optical imagery constrain the majority of the remaining strike-slip motion and some dip-slip motion above 5-km depth. The InSAR imagery from both flight directions constrain deeper slip. Within the lidar footprint, differential topography dominantly constrains fault slip above 7 km (Figure 3c, dashed lines). Because the optical imagery constrain near- and far-field slip, the imagery have a fairly constant resolving power with depth and resolve less shallow slip than does the differential topography.

#### 4.3. Regularization

As commonly observed, the regularization choice impacts the inferred slip distribution. Increasing the amount of regularization (i.e., higher  $\lambda$ ) decreases the maximum slip for both sets of earthquake source inversions (Figure 4b). For the range of regularization values, the lidar-optical-InSAR inversion resolves a greater maximum slip than does the optical-InSAR inversion. This may reflect that the greater density of differential lidar topography near the fault require more concentrated slip and a higher slip magnitude. The moment release migrates from the Hinagu to Futagawa Fault with increasing regularization (Figure 4c). The lidar-optical-InSAR inversion places additional moment release on the Hinagu Fault, possibly because the differential lidar topography requires two overlapping faults near the intersection of the Futagawa and Hinagu Faults. In contrast, the optical and InSAR (Jiang et al., 2017) data sets can be well modeled with a single curving fault. Huang et al. (2017) observed that the regularization affects the depth profile of slip for the 2010 M7.2 El Mayor-Cucapah earthquake. It remains important to test the impact of the regularization in joint slip inversions, particularly as more data types are ingested into slip inversions.

#### 4.4. Shallow Fault Slip Behavior

We examine the median slip versus depth for the Hinagu (Figure 4d) and Futagawa Faults (Figure 4e) and the entire earthquake (Figure 4f) for the lidar-optical-InSAR (blue) and optical-InSAR (red) slip inversions. The shallow slip deficit along the Hinagu fault from the lidar-optical-InSAR slip inversion may indicate that the earthquake did not yet have sufficient energy to rupture through the velocity-strengthening portion of the shallow crust.



**Figure 4.** L-curve showing solution seminorm versus residual for a variety of smoothing values ( $\lambda$ ) for the lidar-optical- Interferometric Synthetic Aperture Radar (InSAR; squares) and the optical-InSAR (triangles) slip inversions. Colors show (a)  $M_w$ , (b) maximum slip, and (c) ratio of moment release on the Hinagu Fault to the entire earthquake. The black circle and curve symbol indicate the best slip model and uncertainty. Median slip (blue and red line) versus depth for the (d) Hinagu Fault, (e) Futagawa Fault, and (f) entire earthquake. The cyan and pink clouds show the 1- $\sigma$  slip range for the lidar-optical-InSAR and optical-InSAR slip inversions, respectively. Map view images of the slip distribution from (g) the lidar-optical-InSAR and (h) the optical-InSAR source inversion in this study as well as from (i) Asano and Iwata (2016) and (j) H. Kobayashi et al. (2017). Dots show modeled slip along subfaults, and the lines contour the fault slip. The black circle in Figure 4g is the 14 April  $M_{jMA}$  6.5 foreshock epicenter location.

Both the lidar-optical-InSAR and optical-InSAR inversions show similar behavior for the Futagawa Fault: a median slip of  $\sim 2$  m at depths of 1–4 km and a decrease in slip within the upper 1 km of the crust. We interpret this observation to reflect a slip deficit along the primary fault trace yet not a shallow strain deficit in the 3-D fault volume. Approximately half of the total shallow deformation



was accommodated off the principal fault, and the region of inelastic deformation straddled the fault by 250 m (Scott et al., 2018). The 1905 Tsetserleg-Bulnay (Choi et al., 2018), 1999 Izmit (Rockwell et al., 2002), and 2013 Balochistan (Vallage et al., 2015) earthquakes produced similar off-fault deformation. Likely, the off-fault deformation was accommodated as volume change (Scott et al., 2018) and as slip along secondary faults in a flower-like structure that was not explicitly included in the fault geometry. In the slip inversion, the shallow and off-fault deformation was mapped as deeper on-fault slip, resulting in an apparent shallow slip deficit. Further, inelastic deformation produces a lower strain than does elastic deformation (Kaneko & Fialko, 2011), suggesting that a portion of the apparent shallow slip deficit reflects the assumed rheology. Future work should focus on using an inverse modeling approach to solve for strain within the 3-D fault volume (Mossop & Segall, 1999; Okada, 1985) in addition to slip along individual faults.

## 5. Conclusions

We develop the first lidar-optical-InSAR earthquake source inversion that resolves slip throughout the seismogenic crust. We quantify depth-dependent variations in fault slip, which are important for understanding the strain budget of the shallow crust. The surface deformation produced by future earthquakes is likely to be recorded by hybrid data sets with varying spatial distribution and sensitivity to the 3-D deformation field. Such joint inversions not only will provide a new opportunity to learn about the behavior of the shallow fault zone but will also present challenges such as those discussed here. We discuss new approaches and model refinements for performing coseismic slip inversions using near-field observations. We learn the following: (1) The model fault geometry must follow the surface trace at a scale appropriate for the finest-resolution data. (2) The amount of regularization impacts the inferred fault slip. (3) Off-fault deformation may be incorrectly interpreted as deeper and on-fault slip. Future work should consider approaches for directly accounting for off-fault deformation in the 3-D fault volume.

## Acknowledgments

C. Scott was supported by the NSF Postdoctoral Fellowship 1625221 and by the School of Earth and Space Exploration at Arizona State University. J. C. and Y. K. were funded by IRSN and the Tosca-CNES Program. E. N. was supported by the Canada Research Chair program and by the Natural Sciences and Engineering Research Council of Canada through Discovery Grant 2017-04029. We thank Editor Lucy Flesch and two anonymous reviewers for constructive comments. The lidar and InSAR data are published and available from Chiba (2018a, 2018b) and Jiang et al. (2017). The Sentinel-2 data are freely available from the European Space Agency (<https://scihub.copernicus.eu/dhus/#/home>) and can be processed using the open-source software package MicMac.

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