

# PROCEEDINGS OF THE TWENTY-SEVENTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

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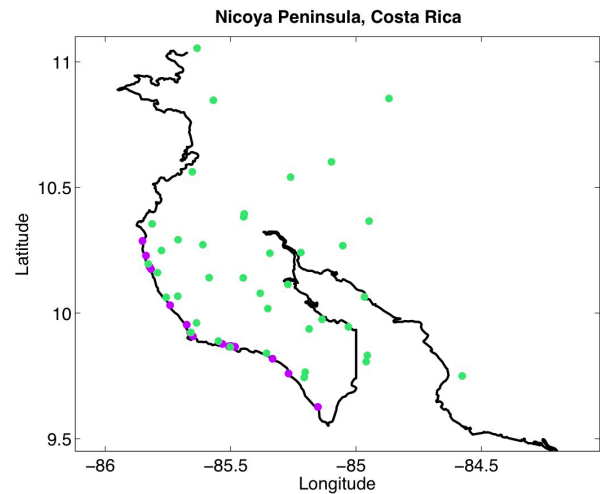
# MODELING COSEISMIC SLIP OF THE 2012 NICOYA PENINSULA EARTHQUAKE, COSTA RICA: ROLES OF MEGATHRUST GEOMETRY AND SURFACE DISPLACEMENT

**PAULA BURGI**, Smith College  
**Research Advisor:** Jack Loveless

## INTRODUCTION

Due to the short and timely seismic cycle of megathrust earthquakes under the Nicoya Peninsula, Costa Rica, the 2012 earthquake was anticipated and exceptionally well-recorded (e.g., Yue et al., 2013; Protti et al., 2014). This research analyzes the discrepant coseismic geodetic and coastal geomorphic observations, as well as the inversion parameters used to constrain the location and magnitude of coseismic slip.

Geomorphic measurements of vertical coseismic deformation were taken along the southwest coast of the peninsula (Fig. 1), showing maximum values of  $65 \pm 20$  cm (Marshall et al., 2013; Protti et al., 2014). Three-component GPS data were recorded throughout the peninsula (Fig. 1), including locations within a kilometer of the southwest coast, and revealed maximum uplift values of  $53 \pm 0.8$  cm (Protti et al., 2014). Although most geomorphic measurements are consistent with the nearest geodetic measurement within reported uncertainties, the geomorphic measurements are consistently larger. These two data sets can be used to explore how differences in uplift measurements affect the estimated slip distribution, and to examine the nature of local heterogeneities in surface displacement revealed by the dense coastal geomorphic measurements.



*Figure 1. Outline of the northwest Costa Rica, including the Nicoya Peninsula (black line). Locations of surface displacement measurement due to the 2012 Nicoya Peninsula earthquake shown in green (GPS stations) and purple (Geomorphic locations).*

The extensive geodetic network and geomorphic surveys, combined with the Nicoya Peninsula's unique position directly overlying the megathrust seismogenic zone, present an excellent opportunity to develop a high-resolution model of slip during the 2012 earthquake. Several slip models for this and other Nicoya Peninsula earthquakes have been produced using varying methods (e.g. Marshall and Anderson, 1995; Yue., 2013; Protti et al., 2014). In the context of this analysis, an inversion model relates displacement on the surface to slip on the subduction interface in an elastic half-space. The two physical inputs of this model are plate interface geometry and surface displacements. The plate interface is modeled as a plane or surface that contains the dislocation on which coseismic slip is calculated, and is particularly

crucial in the case of the 2012 Nicoya Earthquake as the location of the earthquake was so proximal to the peninsula; minor changes in the interface geometry can have significant effects on the estimation of coseismic slip. Surface displacements are 1, 2, or 3 component vectors that measure deformation induced by the Nicoya earthquake. The geodetic and geomorphic datasets described above can be combined or isolated to assess how differing inputs change the estimated slip distribution.

## DATA AND METHODS

### Surface Displacement

This research analyzes data from two independent records of coseismic deformation: geodesy and coastal geomorphology.

Three-component coseismic geodetic observations were obtained from 18 continuous and 21 campaign GPS stations throughout the Nicoya Peninsula and northeast Costa Rica (Fig. 1). These displacement data were processed and published in Protti et al. (2014).

Preseismic and postseismic coastal geomorphology surveys were taken in July of 2012 and two weeks after the earthquake in mid-September of 2012, respectively (Marshall et al., 2013). The elevation differences between these surveys were determined using tide measurements, and corrected for wave run-up and post-seismic activity to isolate coseismic uplift using methods described by Marshall et al. (2013) and Protti et al. (2014). Although they agree within error, the geomorphic vertical displacements are on average 0.15 m greater than that of the closest geodetic station. Spatially, there is nearly a 2:1 ratio of geomorphic to geodetic measurements along the southwest coast of the Nicoya Peninsula. Importantly, all geomorphic surveys were recorded at the shoreline, whereas only three of the GPS stations are within 1 km of the coast.

### Plate Interface Geometry

Previous work on fault geometry emphasizes its importance in estimating coseismic slip from surface deformation data (Hayes et al., 2009; Moreno et al., 2012; Moreno et al., 2009; Resor, 2003). This

research analyzes two representations of plate interface geometry: A segmented plane constructed from a series of planes with uniform strike but increasing dip (Geometry P), and a strike-and-dip-variant surface (Geometry S). All geometries are composed of triangular elements, in accordance with the particular uniform elastic half-space inversion algorithm that is used. Geometry P, comprising planes with uniform strike, is unable to capture dip-parallel subtleties or any strike-parallel variation.

Geometry P was based on the interface model of Yue et al. (2013), parameterizing the interface using 17 strike-parallel x 15 dip-parallel 7.5 x 7.5 km subfaults of increasing dip with depth, with a total area of  $3.68 \times 10^4 \text{ km}^2$ . A similar density of elements was constructed out of these parameters using triangular rather than rectangular elements. Because Yue et al. (2013) use this segmented plane geometry to estimate the slip distribution the 2012 Nicoya Peninsula earthquake using seismic waveform and GPS data, this geometry was chosen to permit comparison the results of Yue et al. (2013).

Geometry S was parameterized by the USGS subduction zone model Slab1.0 (Hayes et al., 2012). This model is a 3-dimensional surface with 1319 elements with an average size of  $30 \text{ km}^2$  and total area of  $4.21 \times 10^4 \text{ km}^2$ . Consideration of along-strike and down-dip variations in megathrust geometry represents a substantial difference between this work and previous estimates of coseismic slip (Yue et al., 2013; Protti et al., 2014) and allows for the exploration of how the fault surface geometry affects the slip distribution.

### Inversion Methods

All analysis was done using MATLAB, a technical computing software program. Observations of coseismic displacement were inverted for slip on the subduction megathrust using elastic dislocation theory. Meade (2007) gives the relationship between slip on the triangular elements used to represent the plate interface geometry, representing dislocations embedded in a homogeneous elastic half space, and displacement at the surface. Because there are fewer displacement observations than estimated slip vector components, I impose a constraint that slip



must be spatially smooth. The enforcement of this constraint was set such that normal-sense slip was at most 10% of peak reverse-sense slip. The up and down dip extents of the modeled fault geometry were constrained to have zero slip in order to prevent discontinuous slip distributions around model edges. The inversion parameter combinations are shown and denoted in Table 1, along with model results.

|   | <b>Geometry P</b>   | <b>Geometry S</b>   |
|---|---|---|
| <b>GPS<br/>2-Component</b>                | Model 2P<br>$M_w = 7.6$<br>$r_h = 0.021$ m<br>$r_v = 0.053$ m | Model 2S<br>$M_w = 7.7$<br>$r_h = 0.038$ m<br>$r_v = 0.093$ m |
| <b>GPS<br/>3-Component</b>                | Model 3P<br>$M_w = 7.6$<br>$r_h = 0.022$ m<br>$r_v = 0.035$ m | Model 3S<br>$M_w = 7.7$<br>$r_h = 0.031$ m<br>$r_v = 0.033$ m |
| <b>GPS<br/>3-Component<br/>+ Geomorph</b> | Model 4P<br>$M_w = 7.6$<br>$r_h = 0.022$ m<br>$r_v = 0.079$ m | Model 4S<br>$M_w = 7.7$<br>$r_h = 0.023$ m<br>$r_v = 0.103$ m |

*Table 1. Each table cell represents an inversion model computed for the 2012 Nicoya Peninsula Earthquake, using different combinations of surface displacement (rows) and plate interface geometry (columns). The surface displacement data include two-component GPS (north and east displacements), three-component GPS (north, east, and vertical displacements), and a “four-component” combination, comprised of three-component GPS plus geomorphic data (vertical component only). Geometry P represents the plate interface geometry of a series of strike-constant segmented planes with increasing dip, used by Yue et al. (2013). Geometry S is a strike-and-dip variant surface modeled from the USGS Slab1.0 geometry (Hayes et al., 2012). Each cell of Table 1 contains the inversion model shorthand, its calculated moment magnitude  $M_w$ , and the horizontal and vertical residuals of predicted surface displacement.*

## RESULTS

Table 1 summarizes results for each model. Results are comprised of strike and dip slip on the subduction zone interface, and three-component predictions of surface displacement due to each slip distribution.

The moment magnitude of Model 3P is consistent with the Yue et al. (2013) and Protti et al. (2014) estimations of  $M_w=7.6$ . Model 3S, however, estimates an earthquake of  $M_w=7.7$ . Figures 2a and 2b show the difference in depth between the planar geometries and Geometry S. On average, the Geometry P and the Protti et al. (2014) geometry are 5.2 km and 7.2 km shallower than Geometry S in the region with slip  $> 2$  m. In comparing the Protti et al. (2014) geometry and Geometry P, the Protti et al. (2014) geometry is similarly composed, with a series of strike-constant planes of increasing dip, but has a larger total area, comparable to the area of Geometry S.

The estimated slip distribution and surface displacements predicted by Models 2S and 3S are shown in Figures 3a - 3d. Between Models 3S and 4S, there is little spatial variation, and the maximum magnitude difference in estimated slip is  $3.04 \times 10^{-4}$  m. The estimated slip distributions of Models 2S and 3S have a larger spatial difference, where Model 2S estimates more spatially concentrated, higher magnitude slip. These two slip distributions, estimated without using geomorphic observations as formal constraints, were used to predict the surface displacement at the location of geomorphic measurements, displayed in Figures 4a and 4b.



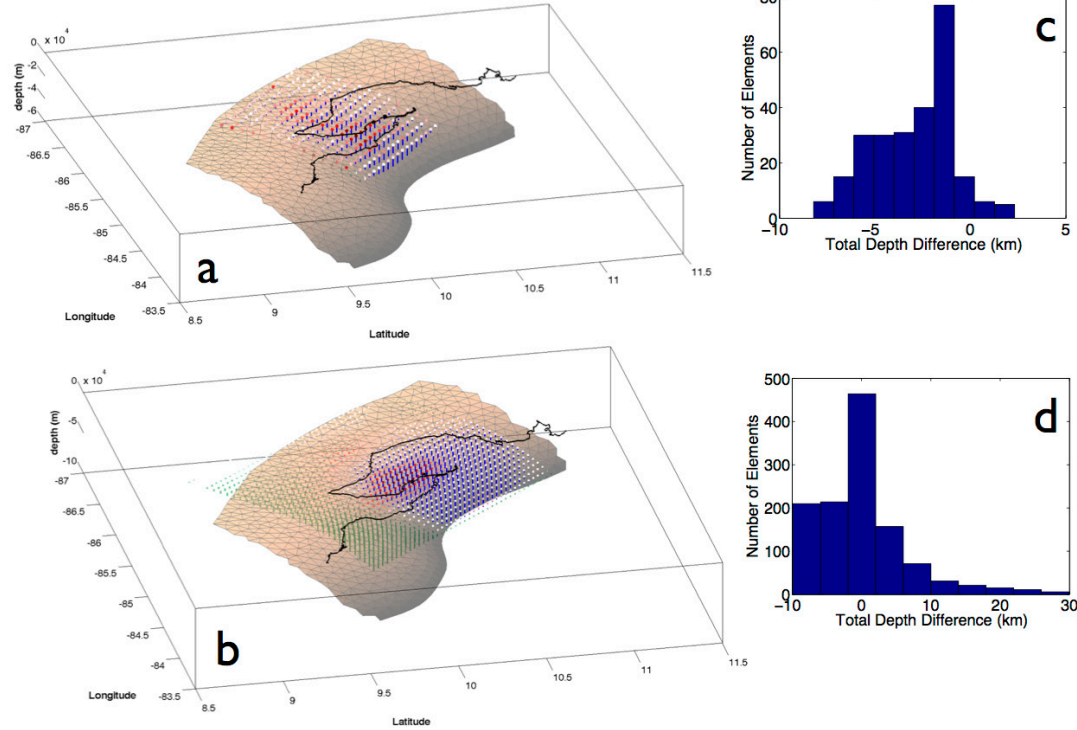


Figure 2. Illustration of Geometry S and its geometric differences between Geometry P (a) and the Protti et al. (2014) geometry (b), as well as their respective slip distributions. Blue bars extend above Geometry S to circles that represent shallower elements of the respective geometry, and green bars below to circles representing deeper elements. The white-red color gradient of the circles represent the published slip distribution for each geometry. The copper-colored gradient on Geometry S represents depth. Parts (c) and (d) are histograms representing the distribution of depth differences.

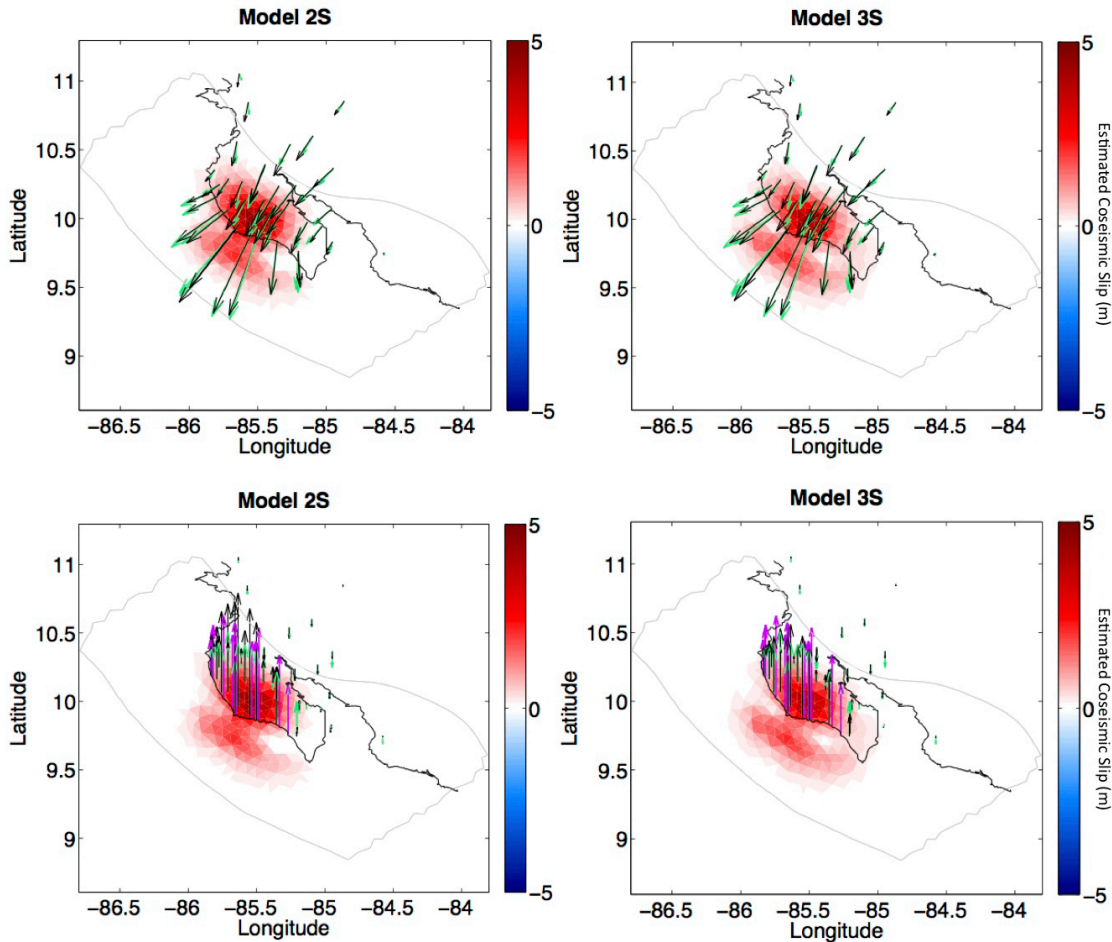


Figure 3. Each panel shows the estimated slip distribution in a red-white gradient on Geometry S. The full geometry is outlined in grey. The northwest coast of Costa Rica, including the Nicoya Peninsula, is outlined in black. Parts (a) and (b) are Models 2S and 3S respectively, and show horizontal measurements of GPS displacement as green arrows, and predicted GPS displacements as black arrows. Parts (c) and (d) are also Models 2S and 3S respectively, and show vertical GPS measurements in black, vertical prediction of GPS locations in green, and geomorphic measurements in purple.

## INTERPRETATION

The results from this research allow for two main interpretations: 1) The representation of plate interface geometry affects the magnitude of coseismic slip; and 2) Geomorphic measurements of coseismic vertical displacement correlate more strongly to the model prediction than the closest geodetic measurements.

### Geometric Analysis

To analyze the influence of the plate interface geometry on estimated coseismic slip, only three-component GPS surface displacements were used. The consistency in slip distribution between Model 3S and published values (Yue et al., 2013) suggests that model results are not dependent on differences in input data (Yue et al. use seismic waveform and GPS data) or inversion techniques (Yue et al. use dislocations embedded in an layered space with depth-varying elastic properties). The incongruence in moment magnitude between the Model 3S estimation ( $M_w=7.7$ ) and the published values in Yue et al. (2013) and Protti et al. (2014) (both  $M_w=7.6$ ) is consistent with the depth differences between Geometries P and S, as the segmented plane geometry lies above  $\sim 5.2$  km above the Slab1.0 geometry (illustrated as blue bars in Figure 4a and 4b), thus requiring a smaller amount of coseismic slip to produce a comparable amount of surface displacement. Additionally, Figure 2a and 2b show that the model interface geometry parameterized by Feng et al. (2012) and used by Protti et al. (2014) also lies 7.2 km above the Slab1.0 geometry, consistent with the Model 3S and 3P comparison. The mean residual values of predicted and measured three-component displacement for Models 3S and 3P are 0.05 m and 0.04 m, respectively. The similarity in mean residual displacement indicates that Model 3S and 3P fit the data nearly equally well. Differences in fitting may be due to unproportional smoothing values between the models. Figure 2a also displays the slip distribution published in Yue et al. (2013) as colored circles on the segmented plane geometry. This slip distribution shows discontinuous slip on the edges of parameterized geometry, perhaps signifying

that the modeled plate interface is too confining for the inverted surface displacements. However, the Protti et al. (2014) slip distribution shown in Figure 2b has a larger total area, comparable to the Slab1.0 geometry, and still generates a  $M_w=7.6$ , therefore discrediting the size of Geometry P as a significant factor in determining the earthquake magnitude. Thus, a depth difference of  $\sim 6$  km between plate interface geometries estimates an earthquake releasing 1.3 times more moment. Moreover, although both Geometries S and P are models of the subduction zone interface, the novel use of Geometry S as a strike-and-dip variant surface allows for the exploration that heterogeneity in fault geometry may give rise to heterogeneity in the slip distribution.

### Geomorphic Analysis

When compared, Models 3S and 4S have an insignificant difference between their maximum magnitude of slip -  $3.04 \times 10^{-4}$  m. This is due to the greater uncertainty of geomorphic field measurements relative to instrumental geodetic data. To examine the local heterogeneities revealed by the spatially dense geomorphic measurements along the coast, we examine vertical displacements predicted at geomorphic locations by Model 2S and 3S, shown in Figures 4a and 4b. The mean vertical GPS residuals for Model 2S and 3S are 0.22 m and 0.08 m, where both models generally overpredict GPS-measured uplift. The mean vertical geomorphic residuals for Models 2S and 3S are 0.12 m and 0.09 m, where Model 2S generally overpredicts, and Model 3S generally underpredicts geomorphic measurements. Model 2S displays an overall preference for vertical displacements significantly larger than those measured in either dataset. With the inclusion of vertical GPS data in Model 3S, the predicted vertical displacement undergoes an average decrease of 45% relative to Model 2S predictions. Thus, Model 3S sensibly reduces the misfit to vertical GPS, and simultaneously fits geomorphic measurement more accurately than the average 0.15 m discrepancy the geomorphic and geodetic datasets.

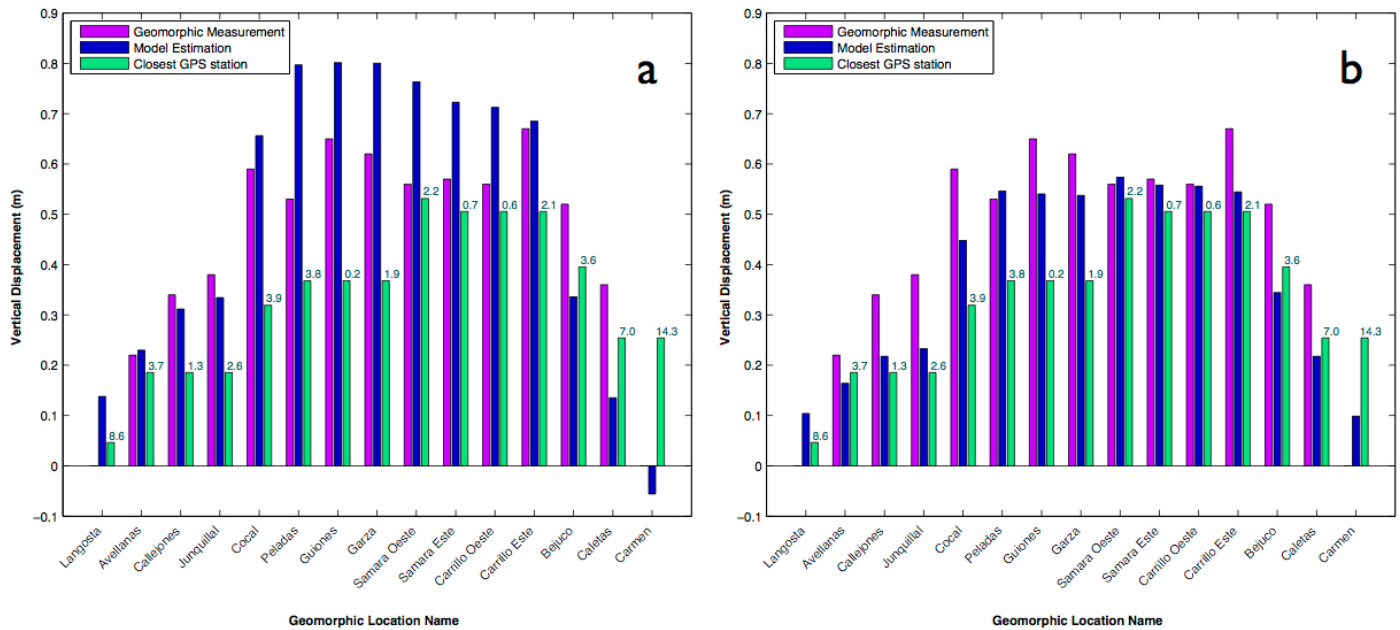


Figure 4. (a) Predicted surface displacement for Model 2S, and (b) predicted surface displacement for Model 3S. The x-axis is labeled with names of each geomorphic location, and the y-axis is vertical displacement due to coseismic slip in meters. Model predictions for the geomorphic sites are shown as blue bars, alongside purple bars representing measured geomorphic displacements, green bars representing vertical displacement of the closest GPS station, and the distance in km to the GPS station shown above each green bar.

## CONCLUSION

Geomorphic and geodetic measurements of coseismic surface displacement due to the 2012 Nicoya earthquake are unprecedented datasets due to their location so near to the region of subduction zone slip. This unique situation presents an opportunity for an in depth analysis of the plate interface geometry on which the earthquake occurred, and the surface displacement measurements constraining coseismic slip estimations. Geometry S represents an advance in modeling the 2012 Nicoya earthquake, and is compared to Geometry P and the geometry of Protti et al. (2014). The deeper Geometry S gave rise to a larger estimation of coseismic slip and moment magnitude ( $M_w=7.7$ ), whereas slip estimated on the shallower Geometry P produces a  $M_w=7.6$  earthquake, consistent with published work (Yue et al. 2013; Protti et al., 2014). The surface displacement input did not significantly alter the magnitude of coseismic

slip, but rather its distribution. This is seen in the second component of this analysis, regarding the discrepancy of  $\sim 0.15$  m between the geomorphic and geodetic vertical displacement data. Predictions of vertical displacement using Model 2S exceed both geomorphic and geodetic measurements, likely due to the spatial concentration of slip estimated by the model. Model 3S predictions of surface displacement generally lie between the geodetic and geomorphic observations, and reflect more broadly distributed estimations of coseismic slip. Furthermore, Model 3S narrows the discrepancy between the geomorphic and geodetic vertical displacement data, fitting the local heterogeneity revealed by the geomorphic data more accurately than the geodetic data. Analyzing the roles of model geometry and surface displacement for the 2012 Nicoya earthquake provides valuable information on the importance of model geometry, and useful insights into the accuracy of surface displacement measurements and predictions.

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