The influence of off-fault deformation zones on the near-fault distribution of coseismic landslides

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ABSTRACT
Coseismic landslides are observed in higher concentrations around surface-rupturing faults. This observation has been attributed to a combination of stronger ground motions and increased rock mass damage closer to faults. Past work has shown it is difficult to separate the influences of rock mass damage from strong ground motions on landslide occurrence. We measured coseismic off-fault deformation (OFD) zone widths (treating them as a proxy for areas of more intense rock mass damage) using high-resolution, three-dimensional surface displacements from the 2016 M₇.8 Kaikōura earthquake in New Zealand. OFD zones vary in width from ~50 m to 1500 m over the ~180 km length of ruptures analyzed. Using landslide densities from a database of 29,557 Kaikōura landslides, we demonstrate that our OFD zone captures a higher density of coseismic landslide incidence than generic “distance to surface fault rupture” within ~650 m of surface fault ruptures. This result suggests that the effects of rock mass damage within OFD zones (including ground motions from trapped and amplified seismic waves) may contribute to near-fault coseismic landslide occurrence in addition to the influence of regional ground motions, which attenuate with distance from the fault. The OFD zone represents a new path toward understanding, and planning for, the distribution of coseismic landslides around surface fault ruptures. Inclusion of estimates of fault zone width may improve landslide susceptibility models and decrease landslide risk.

INTRODUCTION
Coseismic landslides are among the most widespread and impactful hazards resulting from earthquakes (e.g., Marano et al., 2010). As such, it is critical to identify and mitigate landslide risks to human life, buildings, and other vulnerable infrastructure prior to major earthquakes. Coseismic landslide susceptibility models (e.g., Xu et al., 2012; Reichenbach et al., 2018) that rely on a combination of geologic, hydrologic, morphologic, and seismologic parameters are used to inform policy makers and emergency management plans. Despite an increasing global catalogue of landslide inventories, regional coseismic landslide models still rely on predictor variables that have major epistemic uncertainties. One of the most important variables that has yet to be sufficiently explained is “distance to surface fault rupture,” which has been used to account for the higher density of coseismic landslides commonly observed near surface-rupturing faults in coseismic landslide inventories (Xu et al., 2012; Fan et al., 2019; Massey et al., 2020).

This higher incidence of landslides near faults has been attributed to two broad categories of physical processes: (1) stronger ground motions that attenuate with increasing distance from seismic sources (Meunier et al., 2007; Tatard and Grasso, 2013), and (2) geologic conditions and seismic site characteristics resulting from lithologic contrasts, topography, and rock mass damage near faults (Ben-Zion and Sammis, 2003; Kim et al., 2004; Meunier et al., 2008; Gallen et al., 2015; Peacock et al., 2017; Wang et al., 2019). Defining the influence of each broad category, and the variables within them, is challenging and has limited the utility of “distance to fault” as an empirical parameter (Gallen et al., 2015; Parker et al., 2015; Reichenbach et al., 2018).

Advances in quantification of coseismic off-fault deformation (OFD) following earthquakes (e.g., Quigley et al., 2012; Zinke et al., 2014, 2019; Milliner et al., 2015, 2016) provide the opportunity to test the influence of OFD on coseismic landslide distributions. OFD is defined as secondary faulting, warping, granular flow, and other brittle deformation that distribute slip off the primary fault plane during earthquakes, producing permanent tectonic coseismic strain (McGill and Rubin, 1999; Milliner et al., 2015). Coseismic strain contributes to cumulative rock mass damage, but, in a positive feedback loop, this damaged rock mass is more likely to experience greater coseismic strain (Ostermeijer et al., 2020). Consequently, the area of OFD about the fault, or the OFD zone, might approximate an area of reduced rock mass strength that amplifies seismic waves and predisposes slopes to fail under lower stresses (Kim et al., 2004; Parker et al., 2015). Effectively, the OFD zone may serve as an approximation of the local site characteristics that influence coseismic landslide distributions near the fault.

We calculated static surface displacement fields from the 2016 M₇.8 Kaikōura (South Island, New Zealand) earthquake and estimated the width of the OFD zone around 14 surface-rupturing faults. We then compared the decrease in landslide density with increasing distance from surface fault rupture, using the latest 2016 Kaikōura earthquake landslide inventory (Massey et al., 2020), to the extent of the OFD zone and ground motion attenuation models published for the Kaikōura earthquake. In the absence of constraints on coseismic ground motions close to faults, we cannot separate the effects of decreased rock mass strength from enhanced shaking associated with trapped seismic waves or lithologic contrasts. However, using the OFD zone, we can compare the landslide density response to (1) “rock mass damage effects,” including both locally enhanced ground motions and decreased rock mass strength, and (2) the attenuation of ground motions, which appears to influence landslide occurrence further from faults.

2016 KAIKOURA EARTHQUAKE AND COSEISMIC LANDSLIDES
The 2016 M₇.8 Kaikōura earthquake initiated on the Humps fault (Fig. 1). The rupture

propagated to the northeast, across slow-slip-rate (∼1 mm/yr) faults of the North Canterbury Domain (NCD) and onto the faults of the Marlborough fault system (MFS; Hamling et al., 2017; Litchfield et al., 2018), which have much higher slip rates (up to ∼25 mm/yr).

During the 2016 event, surface ruptures were observed on 20 onshore and offshore faults with a range of orientations and relative motions (Fig. 1; Litchfield et al., 2018; Zinke et al., 2019). The greatest surface slip occurred on the Papatea, Jordan, and Kekerengu faults in the MFS (up to 12 m lateral and 8 m vertical); other MFS faults with documented surface rupture include the Manakau, Upper Kowhai, and Snowflake Spur faults in the Seaward Kaikoura range (Fig. 1; Litchfield et al., 2018; Zinke et al., 2019). In the NCD south of the Hope fault, the Humps, Leader, Conway-Charwell, Stone Jug, Hundalee, and Whites faults ruptured to the surface (Fig. 1; Litchfield et al., 2018). Slip on NCD faults was lower (up to ∼3.5 m vertical and lateral) than slip on MFS faults.

The Kaikoura earthquake triggered nearly 30,000 landslides over an ∼10,000 km² area. Approximately 60% of failures occurred on the steep slopes of the Seaward Kaikoura Range (Fig. 1), which is composed of pervasively fractured Early Cretaceous graywacke sandstones and mudstones of the Pahau terrane of the Torlesse Supergroup (Rattenbury et al., 2006). Elsewhere, landslides were concentrated within Late Cretaceous–age to Tertiary-age sedimentary units and unconsolidated Quaternary units (Rattenbury et al., 2006). No direct landslide-related fatalities were recorded from the event, but landslides formed 196 dams and blocked arterial roads and railways for months (Dellow et al., 2017).

Logistic regression models suggested that, in order of importance, the independently tested parameters of geology, mean slope, distance to surface fault rupture (“distance to fault”), local slope relief, peak ground velocity, and mean elevation contributed significantly to the locations of landslides during the Kaikoura event (Massey et al., 2020). The “distance to fault” variable is the third most important and the least understood parameter.

OFF-FAULT DEFORMATION (OFD) ZONE WIDTH

We measured three-dimensional surface displacements over a 25 m grid using point cloud data generated from pre- and post-Kaikoura earthquake optical aerial imagery and a 50 × 50 m windowed implementation of the iterative closest point algorithm (Diederichs et al., 2019; Howell et al., 2020). Using the displacement field, we mapped simplified “main” fault traces for 14 major surface ruptures, which generally coincided with previously mapped traces (e.g., Litchfield et al., 2018; Zinke et al., 2019). Swath profiles 400 m wide and 2 km long, oriented perpendicular to the fault strike, were centered along the fault traces at 500 m intervals. For
each swath, we produced separate displacement profiles in each of the east, north, and vertical components. We removed noise from identifiable sources (e.g., landslides, fast-growing trees) manually and excluded sites from our analysis where we were unable to resolve displacements due to excessive noise. The width of distributed coseismic displacement around the fault was visually estimated for each displacement component profile as the point on either side of the fault at which the displacement field settled into the background total displacement (Milliner et al., 2016; Zinke et al., 2019). At each site, the component exhibiting the widest distribution of displacement across the fault was used to define the total extent of coseismic OFD within the swath profile (Fig. 2A). As a conservative estimate of the OFD zone between profiles, we then connected profile swaths on individual faults using straight lines between adjacent profiles (Fig. 2B). The resulting variable-width polygon defined the widest area of on-fault permanent coseismic strain around the 2016 surface ruptures.

In total, we estimated the OFD zone at 214 locations across 14 primary surface ruptures (Fig. 2C). Surface ruptures in the northern MFS region (Kekerengu, Jordan, Papatea, Upper

Figure 2. (A) Fault ruptures and estimated widths of off-fault deformation (OFD) for the North Canterbury Domain (NCD) on the South Island of New Zealand. (B) Example of the OFD zone interpolated between measured swaths for the Humps and South Leader faults. (C) Box and whisker plots showing OFD width distributions by fault from northeast to southwest. Colors are coordinated with panel A. MFS—Marlborough fault system.
Kowhai, Manakau, and Snowflake) exhibit an average OFD width of \( \sim 500 \) m, compared with \( \sim 600 \) m for faults in the southern NCD region (Whites, Stone Jug, Conway-Charwell, Leader, Humps, and Hundalee). OFD widths ranged from \( \sim 50 \) m to \( \sim 1500 \) m and did not approach the 2 km length of the profile swath in any location.

The OFD zone was locally variable across the components of displacement and along fault traces. This variability likely resulted from factors including lithology and thickness of any overlying sediment, near-surface fault geometry and kinematic variability along strike, slip partitioning over several fault strands, and interaction between faults at depth (Zinke et al., 2014).

### LANDSLIDE DENSITY AND FAULT DISTANCE

We used a 32 m gridded version of the 2016 Kaikoura coseismic landslide inventory (Massey et al., 2020) to calculate landslide source area density within OFD zones and regularly spaced (50 and 200 m increments out to 15 km) buffers around surface fault ruptures in the Kaikoura region (Fig. 3).

There was a gradual decrease in landslide density from 1.6% at 1000 m to 0.3% at 15,000 m (1.3% decrease over 14 km), which mirrored the attenuation of observed and modeled horizontal peak ground accelerations (PGAs, from a hybrid broadband ground motion simulation; Bradley et al., 2017) with increasing distance from the fault (Fig. 3A). However, we observed a sharp increase in landslide source area density from 1.6% at 1000 m to 3.3% at 150 m (1.7% increase around fault ruptures in the Kaikoura region).

Figure 3. Landslide density for the 2016 Kaikoura earthquake (South Island, New Zealand). (A) Landslide density (percent of area covered by landslide source) and horizontal peak ground acceleration (PGA) (Bradley et al., 2017) relative to fault distance. Solid black line represents 50 m bins of fault distance from 0 m to 15,000 m (i.e., 0–50 m, 50–100 m, etc.); dashed black line represents 200 m bins of fault distance; and blue line represents 50 m bins of fault distance exclusively within the off-fault deformation (OFD) zone to 650 m. (B) Zoomed-in view of panel A from 0 m to 1000 m. (C) Graph of landslide density and mean slope (orange) relative to fault distance in 200 m bins. Major topographic features contributing to the distribution of slope with distance from the fault are labeled. (D) Graph of general landslide (LS) density (dashed black line), landslide density within the Torlesse Supergroup graywacke (orange line), and landslide density within all other geologic units (blue line) relative to fault distance.
over 1 km; Figs. 3A and 3B). This increase in landslide density did not correlate with any marked increase in slope (Fig. 3C), local slope relief (Fig. S7 in the Supplemental Material), or modeled PGA (Fig. 3A; Bradley et al., 2017) within 1000 m of surface-rupturing faults, but it could still have resulted from nonlinear attenuation not captured by modeled PGA or a different frequency content of shaking near the faults.

The rupture of more than 20 faults over ~180 km made it difficult to assess nonlinear earthquake attenuation relationships from the hypocenter for the Kaikōura earthquake (Meunier et al., 2007). However, the modeled PGAs matched well with limited observational ground motion records and represent the current best estimate of near-fault ground motion from the 2016 Kaikōura event. Modeling approaches may never fully capture the true magnitude, frequency, or heterogeneity of near-fault shaking unless they explicitly account for the effects of near-fault rock damage. However, the modeling approach used by Bradley et al. (2017) has actually overestimated fault-proximal (<2 km distance) PGA and peak ground velocity (PGV) where limited records were available (Graves and Pitarka, 2010). Thus, the results suggest that two of the most important influences on slope stability—local slope and PGA—did not exert primary influences on regional landslide densities within 1 km of the fault (Figs. 3A and 3C).

Lithology may partially explain the increase in landslide density with proximity to the fault. In the Kaikōura region, active faults commonly form the contacts between Tertiary “soft rocks,” range-front Quaternary units, and Torlesse Supergroup graywacke (Rattenbury et al., 2006). As a result, while ~70% of the Kaikōura region consists of Torlesse graywacke at the surface, graywacke constitutes a lesser ~55% of surface area near ruptured faults (Fig. 3D). The younger units exhibited much higher landslide density near the fault than did the graywacke bedrock (Fig. 3D). This phenomenon, which may result from amplification due to basin-edge effects (Graves et al., 1998) and impedance contrasts between lithologies, could factor into general “distance to fault” trends here (Fig. 3) and in other earthquakes (e.g., Rault et al., 2019).

INCREASED LANDSLIDE DENSITY WITHIN OFD ZONES

Our results reveal a consistently higher landslide density for individual fault buffers nested within the OFD zone as compared to general distance from fault (Figs. 3A and 3B). The density extended up to ~650 m from the faults and indicates that more landslide terrain is located in the OFD zone per unit area despite a relatively representative distribution of topography (Fig. S6). Though it is difficult to decouple the effects of the OFD zone from the influence of lithologic contrasts, the higher density of landslides in the OFD zone does not appear to be biased by lithology. The OFD zone captures a representative proportion of lithologies and has a higher overall landslide density in both Torlesse and non–Torlesse Supergroup lithologies (Table S1; Fig. S8). Other physical influences like instantaneous (i.e., coseismic) or finite strain, coupled with seismic amplification within the weaker rock mass of the fault damage zone itself, could contribute to the higher incidence of landslides close to faults.

Future fault zone studies may provide a way to decouple the near-fault processes and factors that link OFD to near-fault damage and increased coseismic landslide occurrence. In the near term, however, the observed correlation between the OFD zone and increased coseismic landslide occurrence may, itself, be sufficient to improve landslide susceptibility models.

POSSIBLE IMPROVEMENT ON THE “DISTANCE TO FAULT” PARAMETER

The OFD zone captures a higher incidence of landslides near the fault than is readily explained by “distance to fault” or modeled ground motion attenuation alone. Separate variables for modeled ground motion attenuation and fault width could serve as a more robust replacement for the “distance to fault” parameter. Together, these two variables are more likely to capture the near- and far-field attenuation of ground motion and also account for other near-fault factors like decreased rock mass strength. Even general estimates of fault zone width, from field mapping or geophysical surveys, could be an effective tool for approximating the spatial extent of enhanced coseismic landslide susceptibility near faults. Further statistical and field investigations are necessary to fully evaluate the influence of the OFD zone on susceptibility models; nevertheless, characterization of this zone serves as a novel path toward improving our understanding of coseismic landslides.

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REFERENCES CITED


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