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On- and off-fault deformation associated with the September 2013 M_w 7.7 Balochistan earthquake: Implications for geologic slip rate measurements

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ABSTRACT

The 24 September 2013 M_w7.7 Balochistan, Pakistan earthquake ruptured a ~200 km-long stretch of the Hoshab fault in southern Pakistan and produced the second-largest lateral surface displacement observed for a continental strike-slip earthquake. We remotely measured surface deformation associated with this event using high-resolution (0.5 m) pre- and post-event satellite optical imagery. We document left lateral, near-field, on-fault offsets (10 m from fault) using 309 laterally offset piercing points, such as streams, terrace risers, and roads. Peak near-field displacement is 13.6 $^{+2.5}/_{-3.4}$ m. We characterize off-fault deformation by measuring medium- (<350 m from fault) and far-field (>350 m from fault) displacement using manual (259 measurements) and automated image cross-correlation methods, respectively. Off-fault peak lateral displacement values are ~15 m and exceed on-fault displacement magnitudes for ~85% of the rupture length. Our observations suggest that for this rupture, coseismic surface displacement typically increases with distance away from the surface trace of the fault; however, nearly 100% of total surface displacement occurs within a few hundred meters of the primary fault trace. Furthermore, off-fault displacement accounts for, on average, 28% of the total displacement but exhibits a highly heterogeneous along-strike pattern. The best agreement between near-field and far-field displacements generally corresponds to the narrowest fault zone widths. Our analysis demonstrates significant and heterogeneous mismatches between on- and off-fault coseismic deformation, and we conclude that this phenomenon should be considered in hazard models based on geologically determined on-fault slip rates.

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1. Introduction

Coseismic surface slip, or surface rupture, accompanies most large, > M 6 (Biasi and Weldon, 2006; Bonilla, 1982) continental earthquakes and is the geomorphic expression of shallow seismic moment release in Earth's crust. Because surface slip is readily observed and quantified, coseismic displacements comprise a core dataset for earthquake and near-surface tectonic studies (e.g., Wallace et al., 1984; Zielke et al., 2015). For example, surface slip correlates with earthquake magnitude (Bonilla and Buchanan, 1970; Wells and Coppersmith, 1994) and is the basis for fundamental earthquake scaling relations (Scholz, 1982). There are also important societal implications for understanding earthquake surface ruptures: per-event surface displacements and their long-term analog fault slip rates are essential inputs for earthquake hazard characterization and mitigation (Bryant, 2010; Petersen et al., 2014).

Measurements of coseismic surface displacement along fault ruptures – commonly called surface slip distributions – are routinely collected by field parties soon after large earthquakes (e.g., Crone and Machette, 1984; Gold et al., 2013; Haeussler et al., 2004; Klinger et al., 2005; Sharp et al., 1982). These studies commonly measure displaced geomorphic landforms and cultural features, such as stream channels, terrace risers, ridges, roads, canals, and other curvilinear features. Geologic field studies typically focus on “on-fault” displacements, normally defined as displacement on prominent fault strands at the outcrop scale and within tens of meters from the primary through-going rupture. Natural variability in the geometry of faulted landforms has, in general, precluded documenting “off-fault” deformation over distances greater than tens of meters away from the fault.

In this study we seek to address a fundamental problem in earthquake geology studies: How does surface deformation vary within tens, hundreds, and thousands of meters from a primary surface rupture? There is often a disparity between coseismic displacement values

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obtained by summing on-fault brittle offset (Lawson and Reid, 1908), typically obtained at the outcrop scale and over tens of meters, and distributed off-fault deformation such as rotation and warping extending hundreds of meters or more away from primary surface ruptures. A number of studies have focused on documenting on- and off-fault deformation associated with one or more earthquakes. Salyards et al. (1992) measured rotation recorded by fine-grained magnetic sediments at the Pallett Creek site along the San Andreas fault and concluded that as much as 78% of deformation at the site was distributed over a zone that extended ~45 m from the principal fault trace. Rockwell et al. (2002) used laterally offset linear cultural features associated with the 1999 Izmit and Duzce earthquakes and showed that, on average, 15% of total lateral slip associated with these earthquakes occurred off-fault. By contrast, Rockwell and Klinger (2013) found that there was virtually no off-fault deformation associated with the 1940 Imperial Valley surface rupture. A related suite of studies have examined the cumulative deformation associated with kilometers of displacement (100 s of earthquakes): for example, Oskin et al. (2007) and Shelef and Oskin (2010) documented offset geologic features, such as dikes and inactive faults that record the cumulative result of numerous ground-rupturing earthquakes, and they conclude that off-fault deformation can extend up to 1–2 km from the fault zone with 70% of the deformation concentrated within 100 m of the fault.

Geodetic techniques are a powerful way to document the spatial variation in deformation patterns associated with surface-rupturing earthquakes. A study of the Calico fault by Cochran et al. (2009) used seismic and interferometric synthetic aperture radar (InSAR) observations to show that fault damage is observed over a zone 1.5 km wide, indicating that cracking and yielding of rock extends beyond the primary surface rupture. Numerous researchers using InSAR and GPS to invert for coseismic fault slip have noted a dearth of inferred slip near the Earth's surface, termed the “shallow slip deficit” (Fialko et al., 2005; Simons et al., 2002) that may be accommodated as off-fault deformation (Dolan and Haravitch, 2014). Nissen et al. (2014) found that surface displacements derived from pre- and post-earthquake lidar surveys in Japan appeared to show shallow depletion of slip on the main fault trace, suggestive of near-surface folding or distributed faulting within 200 m of the main surface rupture. Milliner et al. (2015) employed optical pixel correlation of pre- and post-seismic aerial photographs spanning the 1992 Landers earthquake rupture and showed that 46% of the deformation was accommodated off-fault within a ~150 m wide zone. Dolan and Haravitch (2014) compared preexisting datasets of surface displacement measurements to inferred slip at depth for numerous recent earthquakes. Their compilation suggests that the amount of on-fault deformation correlates to fault maturity, ranging from 50 to 60% for an immature fault to 85–95% for a mature fault.

The 24 September 2013 M_w7.7 Balochistan, Pakistan earthquake involved continuous surface rupture along ~200 km of the Hoshab fault. This strike-slip earthquake occurred within the Makran accretionary prism in southern Pakistan (Fig. 1), a region characterized by the intersection of east-west oriented reverse faults that accommodate convergence between Arabia and Eurasia (Platt et al., 1988; White and Louden, 1982) and north-south oriented strike-slip faults associated with left-lateral relative motion between the India and Eurasia plates (Lawrence et al., 1981). In the epicentral region, fault traces form an arcuate network linking the dominantly contracting and shearing regions.

The remote location, inaccessibility, and length of the rupture limit opportunities for systematic field-based mapping of the Balochistan rupture. However, the arid landscape and lack of vegetation or urban development provide ideal conditions to observe surface deformation through remotely sensed imagery. The 2013 earthquake has been investigated using a number of techniques, including pre- and post-event optical and radar pixel tracking and teleseismic waveform inversions (Avouac et al., 2014; Barnhart et al., 2014, 2015; Jolivet et al., 2014). These efforts find that rupture propagated bilaterally on the Hoshab fault, a reactivated reverse fault dipping north 60° ± 15°. Zinke et al. (2014) examined surface deformation associated with the 2013 Balochistan earthquake by comparing on-fault lateral offsets interpreted from 0.5 m WorldView and 5 m SPOT satellite optical imagery to the far-field displacement field calculated based on pixel correlation of Landsat 8 (240 m resolution pixel tracking map). They conclude that 45% of the deformation associated with this earthquake occurred off-fault, or away from the primary surface rupture.

We build upon these efforts by exploiting high-resolution (0.5 m) optical satellite imagery for rupture mapping, displacement measurements, and high-resolution pixel tracking to understand the displacement field associated with the 2013 Balochistan rupture. We map the 2013 surface rupture and measure lateral displacements of geomorphic features along its length using high-resolution commercial satellite imagery (0.5 m resolution WorldView 1 and 2). We place our observations in the context of horizontal surface displacements at length scales up to several kilometers from the fault using previously derived measurements from automated cross-correlation of pre- and post-earthquake images (“pixel tracking,” 5 m resolution map) (Barnhart et al., 2015). To examine how deformation varies in detail along the entire length of a large surface-rupture earthquake we compare results from on-fault displacement mapping (≤10 m from main fault trace(s)), medium-scale measurements (<350 m) of deformed geomorphic markers, and far-field automated pixel correlation methods (generally >350 m from main fault trace(s) (Barnhart et al., 2015)). We also measure the surface width of the coseismic deformation zone apparent in optical imagery. We report along-strike variations in the ratios of deformation at these various length scales, discuss their uncertainties, and interpret the results in the context of frameworks that attempt to tie surficial geologic observations to far-field strain accumulation and rupture processes at depth. Importantly, we find that off-fault deformation is closer to one-quarter (28%) of the far-field value rather than nearly one-half (45%) as previously reported (Zinke et al., 2014).

2. Methods

2.1. Mapping

We used 13 pre- and 17 post-earthquake WorldView 1 and 2 panchromatic, orthorectified, 0.5 m resolution images to map the fault rupture at a scale of 1:10,000. The post-event scenes were acquired between 1 October 2013 and 23 January 2014, 7–114 days following the earthquake (see Fig. S1 in Barnhart et al.(2015)). The lag between the time of the earthquake and image acquisition means that these images capture coseismic displacement, early postseismic deformation (e.g., afterslip), and small displacements that may have accompanied an M_w6.8 aftershock on 28 September 2013. It has been noted in some fault systems that surface displacements due to shallow afterslip may match or exceed coseismic surface displacement, especially for relatively small ruptures or on creeping fault systems (Aagaard et al., 2012; Wei et al., 2015). The contribution of post-seismic deformation to our reported measurements is expected to vary along-strike as the post-seismic interval of acquired scenes varies. We assume that the manual offset detection threshold of the imagery is ~0.5 m based on the ground sample distance. Analysis of spatially overlapping scenes with post-earthquake acquisitions ranging from 1 week to several months after the earthquake reveal no manually detectable offsets, indicating ongoing post-seismic deformation does not impact our observations. Furthermore, post-seismic shallow afterslip is commonly a small percentage of overall coseismic surface displacement in large ruptures (Bürgmann et al., 2002; Kaneko and Fialko, 2011). Nonetheless, we are unable to discriminate between coseismic deformation and post-seismic deformation occurring within the first week of the earthquake; thus, these offsets are also included in our measurements.

Using the post event imagery, we mapped the primary surface rupture and subsidiary fault traces and fractures at a scale of 1:10,000 (Plates 1 and 2, KMZ rupture trace, Supplementary data). To characterize