Inelastic surface deformation during the 2013 M\textsubscript{w} 7.7 Balochistan, Pakistan, earthquake

A. Vallage\textsuperscript{*}, Y. Klinger\textsuperscript{1}, R. Grandin\textsuperscript{1}, H.S. Bhat\textsuperscript{1}, and M. Pierrot-Deseilligny\textsuperscript{2}

\textsuperscript{1}Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Université Paris Diderot, UMR 7154 CNRS, 1 Rue Jussieu, F-75005 Paris, France
\textsuperscript{2}IGN, LOEMI, Université Paris-Est, 73 Avenue de Paris, 94165 Saint-Mandé cedex, France

ABSTRACT

Comprehensive quantification of the near-field deformation associated with an earthquake is difficult due to the inherent complexity of surface ruptures. The A.D. 2013 M\textsubscript{w} 7.7 Balochistan (Pakistan) earthquake, dominated by left-lateral motion with some reverse component, ruptured a 200-km-long section of the Hoshab fault. We characterize the coseismic rupture in detail along its entire length. Optical and radar satellite images are combined to derive the full three-dimensional far-field displacement (115 m pixel size) and the high-resolution 2.5 m pixel horizontal displacement field resulting from the earthquake. We show that the vertical deformation is significant in several locations. The high-resolution near-field horizontal displacement (<1 km around the rupture) reveals inelastic shortening at the fault surface significantly larger than expected from simple elastic modeling. A zone of extension in the hanging wall, as much as 1 km wide, concentrating numerous tensile cracks visible in submeter-scale optical images, compensates for this excess shortening.

INTRODUCTION

Accurate quantification of deformation along earthquake surface ruptures can be difficult due to complexity of the rupture geometry (Klinger et al., 2005; Milliner et al., 2015). When available, detailed ground surface measurements show that surface-slip variations often correlate with geometrical complexities of the surface rupture (Klinger et al., 2006; Klinger, 2010; Wei et al., 2011), distributing coseismic slip through partitioned (Bowman et al., 2003; King et al., 2005) or distributed deformation (Vallage et al., 2014). Effects due to interaction between an upward-propagating rupture and the free surface could also add complexity to the surface rupture (Madariaga, 2003). Even so, surface slip distributions are commonly used to estimate earthquake magnitude (e.g., Wells and Coppersmith, 1994). The apparent discrepancy between slip modeled at depth and slip observed at the surface led some researchers to propose that continental earthquake ruptures are characterized by some shallow-slip deficit related to fault maturity and local sediment thickness (Fialko et al., 2005; Dolan and Haravitch, 2014; Zinke et al., 2014).

On 24 September 2013, the M\textsubscript{w} 7.7 Balochistan earthquake ruptured 200 km of the Hoshab fault in Pakistan (Avouac et al., 2014; Barnhart et al., 2014, 2015; Gold et al., 2015; Jolivet et al., 2014; Zhou et al., 2015; Zinke et al., 2014). Although the rupture propagated bilaterally on a curved, north-dipping fault (45°–75°) with azimuth veering from N200° to N240°, the earthquake is mostly characterized by left-lateral strike slip, with a limited reverse component.

\textsuperscript{*}E-mail: vallage@ipgp.fr

Using 15 m Landsat-8, 2.5 m SPOT-5, Google Earth™ submeter-scale optical images, and TerraSAR-X radar data, we reconstructed the full three-dimensional (3-D) displacement field and the high-resolution displacement field to characterize the near-field deformation along the entire rupture. The rupture trace was also mapped in detail.

MEASUREMENT OF SURFACE DISPLACEMENT FIELD

Figure 1 shows the 2.5 m pixel size horizontal displacement field derived from correlation of preearthquake and postearthquake SPOT-5 satellite images using MicMac (Rosu et al., 2015; http://logiciels.ign.fr/-Micmac_3-), af-
NEAR-FIELD CHARACTERIZATION OF THE RUPTURE

The continuous 2.5-m-resolution horizontal displacement field allows for mapping details of the deformation pattern due to the 2013 event. Figure 2A shows a fault-normal shortening profile (blue curve: stack in a 15-km-long and 100-m-wide box) along the direction perpendicular to the local azimuth of the rupture. This kind of profile is observed in many locations along the southern part of the rupture. For the section located 1 km away or more (herein referred to as far field) from the actual ground rupture, the shape and amplitude of displacement are generally consistent with an elastic dislocation dipping 60° to the north (green curve in Fig. 2A; modeled after Okada, 1992), in agreement with geophysical inversions (Avouac et al., 2014; Barnhart et al., 2014; Jolivet et al., 2014).

Conversely, the section of the hanging wall located directly next to the ground rupture shows an excess of shortening incompatible with simple elastic deformation. Because near-field (0.1–1 km north of the scarp) and far-field (>1 km away from the scarp) deformation need to be reconciled eventually, a zone of distributed extension located in the hanging wall compensates for the extra shortening. In that case, the total relative extension in the hanging wall reaches 4.5 m, over a width of 1 km (Fig. 2A).

In order to assess the along-strike extent of this inelastic deformation in the hanging wall, we systematically measured far-field and near-field displacement on 2000 independent profiles (100-m-wide stacks located every 100 m). For each profile, we measured both the fault-parallel (left-lateral motion positive) and the fault-normal (shortening negative) displacement. Overall, the far-field displacement distribution (Fig. 2B) is in good agreement, both in amplitude and spatial variations, with previously published strike-slip distributions (Avouac et al., 2014; Barnhart et al., 2015; Gold et al., 2015; Zhou et al., 2015; Zinke et al., 2014), yielding an averaged total slip amplitude of 7.3 m, with a maximum of 11.5 m. Despite a significant change of azimuth along strike, strike-slip motion dominates until the end of the rupture, with shortening <3 m. Displacements measured in the near field are slightly larger, due to attenuation...
of elastic displacement with distance (Okada, 1992), with an average total surface slip of 8 m and a maximum of 14 m (Fig. 2C). Near-field fault-normal surface slip, however, shows pronounced differences in amplitude when compared to far-field measurements, locally reaching 6–7 m in shortening. Differences between the near-field and far-field shortening measurements are mostly located along a 110-km-long zone (purple arrow from km 30 to km 140 in Figs. 1, 2C, and 2D) previously identified as missing slip areas (identified in red in top bar of Fig. 2D) by Zinke et al. (2014) based on analyses of geomorphic marker offsets. The lateral slip variability is also larger along this section of the fault, with significant variations occurring both on the fault-parallel and the fault-normal components over only a few kilometers (Fig. 2C). In some of the mapped complex rupture zones (relay zone c2 and paired bend c3; Fig. 2C) the two components are anticorrelated in amplitude with an increase in the fault-normal component when the fault-parallel component decreases. The density of measurements and spatial coherence ensure that this signal is real. These local matches between slip variation and ground-rupture complexity are interpreted as the signature of the fault structure complexity, possibly related to lateral segmentation (Klinger et al., 2006; Wesnousky, 2008; Klinger, 2010). Nevertheless, as the ratio between the near-field and far-field shortening is well above 1 (Fig. 2D) over a 110-km-long zone, it suggests that there is another process at a larger scale. Figure 3 shows an along-strike succession of wide damaged zones, indicated by the pink color where the displacement is mostly perpendicular to fault azimuth, alternating with sections where deformation is more localized, with a sharper transition from yellow to blue indicative of dominant fault-parallel motion. Using submeter-scale optical imagery (Worldview, SPOT-5, and Google Earth), we mapped the entire surface rupture at 1:500 scale, down to decimeter-scale cracks. Damage zones (Gold et al., 2015; Zinke et al., 2014) are characterized by a band of subparallel tensile cracks that spread across the hanging wall, away from the frontal scarp, over distances from a few hundred meters to 1 km. Figure 3B shows the extent of cracking in the hanging wall inside zone f1, affecting the entire sedimentary wedge located between the frontal thrust and the basement outcrop in the background. It is representative of the deformation occurring along the entire length of the distributed deformation zone. The relatively flat topography of the affected area rules out landsliding as a primary cause of cracking. The frontal scarp, which carries most of the shortening, remains very localized and zigzags at the scale of hundreds of meters following local topography. Therefore, it suggests that the thrust fault flattens to a shallow dip when it reaches the surface. In contrast, the strike-slip component does not always localize at the front and instead is distributed over the entire zone of cracking, together with the opening component, making direct measurement of the strike-slip on images (Gold et al., 2015) or in the field difficult. Our measurements show that eventually the total budget of displacement is taken up by the numerous distributed cracks activated by the rupture.

CONCLUSIONS

Figure 3C shows an idealized cross section that reconciles far-field and near-field measurements along the 110-km-long section where we found excess shortening at the fault. Restoration of the 3-D far-field displacements on an averaged 60° north-dipping fault indicates that ~3–4 m of reverse slip took place at depth on the fault plane (Avouac et al., 2014; Barnhart et al., 2014; Jolivet et al., 2014). Such slip would project at the surface into 1.5–2 m of horizontal shortening and ~3 m of uplift, but could not account for the 3–4 m of horizontal shortening that we measured in the near field, directly at the rupture tip. We suggest that this apparent excess of shortening at the surface results from flattening of the fault when it reaches the free surface. This interpretation assumes that the total amount of slip on the fault plane remains constant as the rupture propagates updip, explaining the local increase of the shortening at the surface tip of the rupture. It is likely that deformation related to surficial fault geometry is also enhanced by the effect of the propagating rupture encountering the free surface (Gabchian et al., 2014; Madariaga, 2003; Oglesby et al., 2000), as suggested by large deformation observed in the hanging wall of the A.D. 2011 Tohoku-Oki (Japan) earthquake (Fujie et al., 2011; Kodaira et al., 2012).

Such a change in geometry promotes extension in the hanging wall that is in turn accommodated by the distributed set of tensile cracks observed on images. This interpretation is supported by the observation that, although widespread along the 110-km-long section, the excess shortening feature seems to be found mostly in locations where the rupture propagated at least at a few hundred meters away from the front of the folded basement, through
surfacial unconsolidated sediments (Zinke et al., 2014). We suggest that this distributed deformation results from the oblique mode of rupture, because it is only observed where significant thrusting occurs in addition to strike slip, or in geometric complexities, as pointed out by Milliner et al. (2015).

As near-fault distributed deformation becomes measurable thanks to high-resolution imagery, comparison with broader scale geodetic data (GPS and interferometric synthetic aperture radar) may suggest that actual shallow slip deficit (Fialko et al., 2005) during very large earthquakes may be the exception rather than the rule.

ACKNOWLEDGMENTS

Numerical experiments were performed on the S-CAPAD platform, Institut de Physique du Globe de Paris (IPGP), France. This work was supported by Agence Nationale de la Recherche (ANR) GeoSMEC contract ANR-12-BS06–0016, and the Centre National d’Etudes Spatiales (CNES) TOSCA ISIS programs. We thank B. Holdsworth, J. Hollingsworth, and three anonymous reviewers for insightful comments. This is IPGP contribution #3689.

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Manuscript received 24 August 2015
Revised manuscript received 12 October 2015
Manuscript accepted 14 October 2015
Printed in USA