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Off-fault deformation in regions of complex fault geometries: the 2013, M_w7.7, Baluchistan rupture (Pakistan)

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Key points:

- East-west, north-south, and vertical surface displacement maps are calculated at 0.5 m ground resolution.
- We show the role of off-fault deformation in accommodating surface displacements across two kilometer-scale fault geometrical complexities.
- Total coseismic surface displacement is constant along the study area, despite strong variations in the rupture geometry.

Abstract

Observations of recent earthquake surface ruptures show that ground deformations include a localized component occurring on faults, and an off-fault component affecting the surrounding medium. This second component is also referred to as off-fault deformation (OFD). The localized component generally occurs on complex networks of faults that connect at depth onto a unique fault plane, whereas OFD consists of distributed fracturing and diffuse deformation of the bulk volume, and occurs over scales of hundreds

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of meters to kilometers around the faults. High-resolution optical image correlation presents a unique potential to characterize the complexity of the surface displacements, including on- and off-fault deformations. In this study, we used sub-pixel correlation of 0.5-m resolution optical images to measure the surface displacement field with a <20 cm accuracy for a 30-km long section of the 2013 $M_w7.7$ Baluchistan, Pakistan, rupture. Our results document significant variability in the fault displacements, associated with large proportions of OFD in regions of fault geometrical complexity. Conversely, in regions where the fault geometry is simple, surface deformation is entirely accommodated by the primary faults with 0% OFD. When combining the localized deformation on faults with the OFD, we show that the total surface displacement budget is constant along the strike of the rupture, despite strong variations observed in the rupture geometry. Based on this analysis, we propose an idealized scenario of earthquake surface deformation as a function of the rupture geometrical variations.

Plain language summary

The 2013 $M_w7.7$ Baluchistan earthquake produced a 220 km-long fault rupture in the Makran region in Pakistan. Because it is a military conflict zone, no field observations could be made, and the earthquake was studied exclusively using seismic, GNSS, and satellite data. In this work, we correlate high-resolution (0.5 m) pre- and post-earthquake optical images to measure the 3D ground displacement field for a 30 km-long section of the rupture. This allows us to perform a detailed budget of surface deformation, including displacements on the different faults, and low-amplitude deformation (10^{-3} to 10^{-4}) of the medium up to 1 km from the faults. We show that the distant deformation occurs around the two major fault geometrical complexities present in our study area. In fact, we

measure lower fault displacements across these complexities than across regions of simpler fault geometry. However, when considering both the displacements occurring on the faults and the distant deformation of the medium, we obtain a total surface displacement that is constant along the entire study area. This shows that, in this case, fault geometrical complexity did not prevent the surface deformation from occurring, but favored the distribution of the deformation over wider regions around the faults.

Keywords

Baluchistan, earthquake, rupture, off-fault deformation, diffuse deformation, high-resolution optical image correlation

1. Introduction

The geometry faults has a strong control on the extent of the earthquake rupture (King and Nabelek, 1985; Schwartz and Coppersmith, 1984; Wesnousky, 1988) and on the distribution of slip on- and off-fault (Antoine et al., 2021; Gold et al., 2015; Milliner et al., 2016a; Scott et al., 2018). Geometrical variations in the fault trace, hereafter named “complexities”, locally modify the stress distribution along the fault plane, and eventually impact the propagation of the rupture (Aydin and Du, 1995; King et al., 1994; Mildon et al., 2019, 2016). Complexities are favorable points for earthquakes to nucleate, and can also act as barriers and cause ruptures to stop (Biasi and Wesnousky, 2017; King and Nabelek, 1985; Manighetti et al., 2007; Wesnousky, 2006). They also cause variations in the velocity of the rupture (Bruhat et al., 2020; Duan and Oglesby, 2005; Vallée et al., 2008), which enhance the higher frequency and destructive seismic wave radiations (Bhat et al., 2007; Okuwaki and Yagi, 2018). Moreover, fault geometrical complexity enhances

the distribution of the deformation in the off-fault medium, also referred to as OFD (Griffith et al., 2010; Rockwell et al., 2002). Consequently, the characterization and quantification of the total surface deformation associated with an earthquake are particularly challenging in the case of a complex surface rupture. This potentially produces a bias in estimating the earthquake displacement budget, affecting our understanding of the rupture process and the modeling of the seismic hazard. Finally, because OFD occurs within the rock volume around the faults, it modifies the rheology of the fault zone (Lockner et al., 1991; Vidale and Li, 2003), and impacts the interseismic strain accumulation (Faulkner et al., 2006; Lyakhovsky and Ben-Zion, 2008) as well as the dynamic rupture propagation (Ben-Zion and Ampuero, 2009; Templeton and Rice, 2008). Hence, assessing the part of the surface deformation that is accommodated off-fault, and characterizing the mechanisms involved, are necessary to our understanding of the shallow rupture process.

Application of optical image correlation methods using high-resolution satellite data offers a solution to characterize and quantify the surface displacement field within the fault zone with continuous and dense coverage (*e.g.*, Antoine et al., 2021; Barnhart et al., 2020; Delorme et al., 2020; Milliner et al., 2016a; Vallage et al., 2015; Zinke et al., 2019). It allows characterizing the fault geometry in detail, and quantifying on- and off-fault displacements. Hence, one can identify parameters that control the shallow rupture process and associated surface deformation. For example, it was shown that ruptures often reuse pre-existing faults from the basement, which favors complex fault geometries and widespread distributed surface deformation (Antoine et al., 2021; Teran et al., 2015; Vallage et al., 2016). The obliquity of the pre-existing faults relative to the current

regional stress is also proposed to partly control the distribution of slip in the off-fault medium (Antoine et al., 2021; Vallage et al., 2016, 2014). Moreover, rock lithology (Teran et al., 2015; Zinke et al., 2014) and heterogeneity (Choi et al., 2018), and regional topography (Zinke et al., 2019) affect the way coseismic deformation is accommodated at the surface. Finally, propagation of fault slip to the surface is favored when slip is greater at depth (Lauer et al., 2020), and so is the localization of the surface deformation along the primary faults (Antoine et al., 2021; Gold et al., 2021).

This study applies high-resolution optical image correlation to a 30 km-long section of the 2013 M_w 7.7 Baluchistan, Pakistan, earthquake. This event ruptured a 220 km-long portion of the oblique Hoshab fault that connects, to the south-west, with the eastern Makran subduction range, and to the north, with the Chaman strike-slip fault system. The analyzed section is located at the transition between the two tectonic contexts (Fig. 1a), in a region where two major fault geometrical complexities are observed (Vallage et al., 2015). At a regional-scale, the geometry of the 220 km-long rupture is controlled by folded Miocene-Oligocene sedimentary rocks associated with the Makran accretionary prism. This range results from the collision of Arabia and Eurasia at ~ 3 cm/year (Hatzfeld and Molnar, 2010; Kukowski et al., 2000). Several significant instrumental earthquakes were reported along the subduction zone (*e.g.*, 1945, M_w 8.4, Byrne et al., 1992), but no significant event was reported onshore prior to the 2013 rupture. The Chaman fault system accommodates 3 cm/year of northwards motion of the Indian plate relative to the Eurasian plate through sinistral shearing (Bilham et al., 2019; Ul-Hadi et al., 2013). Until 2013, the largest earthquake known in this area was the 1935 M_w 7.7 Quetta earthquake

(Bilham et al., 2019) that ruptured the Ghazaband fault, located east of the Hoshab and Chaman faults (Fig. 1a).

Deformation due to the 2013 Baluchistan event is mostly strike-slip with a mean left-lateral slip of 6-8 m, and a maximum of 12-14 m (Avouac et al., 2014; Barnhart et al., 2015; Gold et al., 2015; Jolivet et al., 2014; Vallage et al., 2015; Zhou et al., 2015; Zinke et al., 2014). A secondary thrusting component is associated with, on average, 1 m of shortening (Vallage et al., 2015) and 2 m of uplift (Barnhart et al., 2019; Lauer et al., 2020; Zhou et al., 2015, 2018). The rupture initiated on a 65°NW dipping fault, and propagated bilaterally to the north where it stopped after 50 km, when it entered the creeping section of the Hoshab fault (Peterson, 2018; Wang, 2017), and to the south-west where it propagated for 150 km (Avouac et al., 2014; Barnhart et al., 2014). In the middle of the southern part of the rupture (N26.456°, E64.968°), where fault slip is close to its maximum, a kilometer-scale compressional relay zone links two major fault sections (Fig. 1b; Gold et al., 2015; Vallage et al., 2015). This relay is referred to as the C2 complexity, following Vallage et al. (2015) and Lauer et al. (2020). It is also known as the Wahli Kaur step-over (WKS) in Gold et al. (2015) and Barnhart et al. (2015). The C2 complexity constitutes the major focus of this study, together with another nearby complexity called C1 (Fig. 1b, referred to as F1 in Vallage et al., 2015).

Building on the high-resolution surface displacement maps produced for a 30 km-long area of the 2013 rupture centered on the C1 and C2 geometric complexities, we aim at characterizing the relations between fault geometry, variations in the fault displacements, and OFD. We first describe the methodology applied to measure the 3D surface

displacement field. Then, we document the displacement field in the regions of geometrical complexity. Finally, we build a slip budget for the fault parallel-component that includes fault slip and OFD. Based on these new observations and measurements, we show how fault geometry and OFD are deeply inter-connected, describe different possible processes that lead to OFD, and propose an idealized scenario of earthquake rupture barrier that shows the role of OFD in the rupture process.

2. Data and methods

In this study, we use the MicMac open-source photogrammetry software (Rosu et al., 2015; Rupnik et al., 2017) with WorldView and Pléiades images to measure the 3D high-resolution (0.5 m) near-fault surface displacement field for a 30 km-long section of the 2013 Baluchistan rupture (Figs. 1b-d). The pre-earthquake image dataset consists of 6 independent and diachronic WorldView images acquired from August 2011 to December 2012 (Tab. S1). In this dataset, at least two images overlap in each rupture area to allow a stereoscopic view of the ground rupture. The post-earthquake dataset consists of 2 tri-stereo Pleiades image acquisitions (6 images in total; Tab. S1), covering respectively the NE and SW parts of our study area. These images were acquired in September 2016, 3 years after the earthquake, and span ± 3 km in either direction orthogonal to the rupture. Both the WorldView and the Pléiades images have a ground resolution of 0.5 m. In order to orthorectify the images later used for correlation, we compute separate pre- and post-earthquake Digital Surface Models (DSMs) using images acquired respectively before and after the earthquake. These DSMs have a 0.5 m ground resolution, similar to that of the input images, and are also used to assess the vertical deformation due to the earthquake. We use the MicMac photogrammetric tools (Rosu et al., 2015; Rupnik et al.,

2017) first, to calculate the pre- and post-earthquake DSMs, second, to correct the images from viewing angle and topography distortions (orthorectification), and then to measure the horizontal displacement field through correlation of the pre- and post-earthquake corrected images. In each region of our study area, we obtain at least 2 pre-earthquake orthoimages from the orthorectification of the WorldView images, and 3 post-earthquake orthoimages from the orthorectification of the Pleiades images. So, the 6 possible pairs of pre- and post-earthquake orthoimages are correlated and the results stacked, allowing for a reduction in noise and artifacts. The input image resolution is preserved through the orthorectification and correlation process; thus we report a horizontal displacement field with a ground resolution of 0.5 m. Minimum amplitude of the ground displacements that can be detected using the sub-pixel method is 0.05 m (Rosu et al., 2014). Because our data only cover a ~5 km-wide swath spanning the fault, we use the horizontal displacement maps at 2.5 m resolution already available for the entire Baluchistan rupture (Vallage et al. 2015) as a far-field reference to correct our near-fault displacement maps for residual ramps. In detail, we take individual profiles parallel and perpendicular to the fault zone to estimate the plane that best represents the shift between our results and Vallage et al. (2015)'s results. The ramp correction is first performed separately on the NE and SW regions that represent two independent correlation tiles, and then over the entire study area to ensure continuity of the displacement field between the NE and SW regions. Once the maps are corrected from the ramps, the direction of the components are rotated from NE and SW to fault-parallel and fault-normal (Figs. 1b,c, and S1), considering a mean rupture azimuth of N235, estimated for our 30 km-long study area.

Vertical deformation due to the 2013 rupture is then assessed by calculating the vertical difference between the pre- and post-earthquake DSMs. Before that, for each pixel of the pre-earthquake DSM, its horizontal displacement, calculated during the previous step, is taken into account to find its location in the post-earthquake DSM. Then its vertical displacement is calculated (Delorme et al., 2020). This enables us to avoid spurious vertical signals in areas that combine steep topography and large horizontal displacement, and measure only vertical displacements associated with the earthquake rupture.

The final fault-parallel, fault-normal, and vertical displacement maps (Fig. 1b-d), although they were corrected from ramps, still present visible artifacts. This includes vertical stripes due to the WorldView sensor, residual topography artifacts (active fluvial network for the most part), and decorrelation due to the presence of clouds. From profiles in the displacement maps, we estimate that, on average, amplitudes of the residual signal related to linear stripes and topography artifacts remain within 0.20 m. Locally, such artifacts can reach a few tens of centimeters to a few meters in amplitude; however, they are easily distinguishable from tectonic deformations. Thus, they do not prevent us from identifying tectonic deformations of amplitudes approaching 10 cm, and we pay special attention that the profiles used for data analysis and slip quantification do not include such artifacts. In summary, although the theoretical detection threshold using sub-pixel correlation is about 0.05 m according to the resolution of our input images (Rosu et al., 2014), we assess that a more realistic detection threshold here is about 0.10 m. The vertical component of displacement, on its part, inherits the noise present in the DSMs. Vertical uncertainty of the DSMs processed with MicMac is of the order of the spatial resolution (Rupnik et al., 2018), *i.e.* 0.50 m.

Because the Pleiades images were acquired 3 years after the rupture, our displacement maps include 3 years of post-seismic deformation. However, amplitudes of post-seismic deformation measured using Radar Interferometry (InSAR) range from 0.01 to 0.10 m in LOS (Peterson, 2018; Wang, 2017). This deformation consists of large-scale relaxation that does not localize at the fault. Moreover, by correlating both SPOT-6 images acquired 45 days after the rupture, and Pleiades images acquired 1 year after the rupture, with the set of Pleiades images acquired in September 2016 (Tab. S2), we could not detect any post-seismic deformation above our detection threshold (~ 10 cm) that localized on the fault plane (Fig. S2). Hence, if any post-seismic deformation is included in our measurements, it would be below the noise level. Even so, it is possible that part of the measured displacements occurred during the early postseismic period (Brooks et al., 2017; Milliner et al., 2020). However, InSAR and optical data do not have sufficient time resolution to constrain the timing of the deformation within the first days and weeks after the rupture.

In a final step, we derive the two-dimensional curl, dilatational strain, and norm of maximum shear strain from the horizontal displacement maps. With this aim, we first down-sample the EW and NS displacement maps to a resolution of 2.5 m to reduce the correlation noise and avoid spurious high-frequency variations (Antoine et al., 2021). The 2.5 m-resolution maps are then derived into displacement gradient maps using a Sobel gradient operator. The curl corresponds to the anti-symmetric part of the displacement gradient, that relates to rotational patterns. Lagrangian finite strain tensor is derived from the displacement gradient maps using Matlab codes from Allmendinger et al. (2012).

From the strain tensor, we extract the maximum shear strain, that relates to the maximum amplitude of shear strain as a function of λ_1 the maximum elongation, and λ_2 the minimum elongation: $\gamma = \pm(\lambda_1 - \lambda_2) / 2(\lambda_1\lambda_2)^{1/2}$ (Ramsay, 1967). The magnitude of this value does not depend upon the orientation of the shear. We also extract the dilatation that corresponds to the trace of the strain tensor, and is a proxy for extensional and compressional deformations.

3. Results and interpretations

Along our study area, the rupture propagated from NE to SW on two primary curvilinear faults, P1 and P2 (Fig. 1b). The C2 complexity corresponds to the compressional relay zone that links P1 and P2. C1 complexity, however, lies within the trace of P1, and is located about 5 km NE from C2 (Fig. 1b). In the horizontal (Fig. 1b,c) and vertical displacement maps (Fig. 1d), localized deformation appears as a clear-cut transition in the displacement fields (e.g., primary faults P1 and P2 in Fig. 1b-d; Fig. S1c), and correlates for most part with the rupture mapped on SPOT-5 images (Vallage et al., 2015; Fig. 1d). The width of these transitions in the displacement maps is no wider than ~0.2 km. Quite differently, OFD generates patches of gradual variations in the displacement maps that affect large regions (~0.2-1 km) around the primary and secondary ruptures (Figs. 2a, and S1b,c). We note that OFD occurring in the direct vicinity of the faults, also known as damage (Faulkner et al., 2003; Mitchell and Faulkner, 2009), is included within the localized deformation (<200 m from the faults). In this study, we are interested in the large-scale OFD (>200 m) that is most often excluded from surface displacement analysis. In total, the ground displacements across the fault zone reach maxima of 12 m in the fault-parallel component (left-lateral; Fig. 1b), 7.5 m in the fault-normal component

(shortening; Fig. 1c), and 4 m in the vertical component (uplift; Fig. 1d). These values are similar to the near-fault displacement values obtained in Gold et al. (2015) and Vallage et al. (2015). They are also two times larger than the average displacement values derived at larger-scale (Avouac et al., 2014; Barnhart et al., 2014; Gold et al., 2015; Jolivet et al., 2014; Lauer et al., 2020; Vallage et al., 2015), which is coherent with earthquake displacement scaling laws (Manighetti et al., 2005). This also shows that displacements in the near-field can reach larger amplitudes than in the far-field (Gold et al., 2015; Vallage et al., 2015).

Figure 1: (a) Regional context of the Baluchistan earthquake (modified from Avouac et al., 2014). Black polygon corresponds to the area covered by the maps from (b-d). The shape of the polygon is controlled by the footprint of the WorldView and Pleiades images used for correlation. (b) Fault-parallel, (c) fault-normal, and (d) vertical displacement maps at 0.5 m ground resolution for the study area in (a). P1 and P2 indicate the two main fault branches of the rupture in this area that are separated by the C2 complexity. AA' and BB' displacement profiles are presented in Figures 2g and 3d, respectively. Dashed black line in (c) is the projection of P1 with a N232 azimuth across the C1 complexity. Surface rupture map from Vallage et al. (2015) is overlaid on (d).

3.1. Displacement and deformation patterns in the C1 and C2 geometrical complexities

3.1.1. C1 complexity

The C1 complexity consists of a 7 km-long and 0.5 km-wide bend that accommodates, in the NS direction, a 3° anti-clockwise change in azimuth in the trace of primary fault P1 (Fig. 1b-d). C1 is characterized by a large area of distributed shear and extension where numerous fractures were mapped (Vallage et al., 2015; Fig. 1d). Amplitudes of fault-parallel displacements across C1 approach 12 m and are distributed between localized deformation on P1, and OFD for about 100 to 500 m NW of P1 (Fig. 2a). Locally, this area of OFD is bounded in its northwestern part, over a length of ~500 m (Fig. 2a-c), by a secondary fault that accommodates up to 4 m of left-lateral displacements. As a comparison, in this same region, P1 and the OFD zone accommodate 6 m and 2 m of left-lateral displacement, respectively (Fig. 2g, profile AA'). The secondary fault appears clearly in the curl and norm of maximum shear strain maps, supporting the fact that it accommodates left-lateral displacement (Fig. 2d,e); however, it does not appear in the dilatation map, nor we could measure significant fault-normal nor vertical offsets at the fault location (Fig. 2b, c, f), meaning that partitioning of the displacements occurred along that section (King et al., 2005).

Figure 2: Displacement maps for a 3 km-long section of the C1 complexity (Fig. 1b) in (a) the fault-parallel, (b) the fault-normal and (c) the vertical components. Surface rupture map from Vallage et al. (2015) is overlaid in (c). (d) Norm of maximum shear strain, (e) curl and (f) dilatation maps at 2.5 m ground resolution. Profiles are 1-km long and cross a 500-m long secondary fault that developed into the hanging-wall and that accommodated mainly fault-parallel displacement. (g) AA' profile in the fault-parallel (red), fault-normal (green), and vertical (blue) components (see also Fig. 1b for profile location). Positive fault normal offsets correspond to

extension, while negative offsets correspond to shortening. The locations of P1 and the secondary fault are reported with a light grey vertical bar.

Fault-normal and vertical OFD zones are two times wider than the fault-parallel OFD zone. Indeed, they both extend about 1 km NW of fault P1. In the fault-normal component, we measure a positive gradient of displacement in the SE direction, with an increase in the amplitude of 2 to 4 m (Figs. 1c, and 2b,g), correlated with subsidence up to 1.5 m in the vertical displacement map (Figs. 1d, and 2c,g). This pattern highlights extensional deformation within the C1 complexity, and correlates with positive dilatation in our strain maps (Fig. 2f) and cracks in the rupture map (Figs. 1d, and 2c; Vallage et al., 2015). The difference in width between the fault-parallel and fault-perpendicular (fault-normal and vertical) OFD zones reveals a partitioning of the OFD. On one hand, the fault-parallel OFD zone is limited, NW of P1, by the secondary fault (Fig. 2a) that is parallel to the continuation of the P1 fault west of C1 (Fig. 1b,c). On the other hand, OFD in the fault-normal and vertical components of displacement are, by definition, impacted by the along-dip fault geometrical variations. The extensional deformation pattern described previously speaks in favor of a shallow dip angle close to the surface, generating horizontal translation of the hanging-wall towards the SE as well as extension and subsidence within the hanging-wall (Vallage et al., 2015).

3.1.2. C2 complexity

The C2 complexity consists of a 5 km-long and 2 km-wide compressional relay zone that links primary faults P1 and P2 (Figs. 1b-d, and 3a). It has been identified in previous studies as the main complexity of the 220 km-long Baluchistan rupture (Barnhart et al.,

2015; Gold et al., 2015; Lauer et al., 2020; Vallage et al., 2015). South-west of C2, fault P1 branches off from the push-up and dies out about 5 km farther south (Figs. 1b-d, and 3a). North-west of C2, two secondary faults (S4 and S5; Fig 3b) connect to form primary fault P2, extending linearly westward. The push-up includes seven secondary faults that strike either EW or NS and link P1 and P2 (faults S1 to S7; Fig. 3b). Faults S1, S3, S6, and part of fault S4 had not been previously identified on the satellite images (Vallage et al., 2015), although they correspond to well-defined slip discontinuities in our displacement and deformation maps (Figs. 1b, and 3e). Orientations of the secondary faults S1 to S7 can be classified into three categories: mountain range azimuth (\sim N235; red, Fig. 3b,c), NNE-SSW orientation (dark blue, Fig. 3b,c) and ENE-WSW orientation (light blue, Fig. 3b,c). These orientations resemble the ones measured in Vallage et al. (2016) across the C1 complexity, with the NNE-SSW orientation being close to the \sim N216 basement fabric orientation they had identified. Even the westward termination of P1 seems to be influenced by the basement fabric since it veers to strike NNE-SSW after C2 (Fig. 1b, and 3a). This highlights the control of the basement fabric orientation on the development of the secondary fault network in the C2 relay zone.

Displacement profiles across C2 (BB', Fig. 3d) present four displacement offsets and OFD gradients in the hanging-wall and the push-up area. When compared to displacement profiles derived from 2.5 m resolution displacement maps (Vallage et al., 2015; Zhou et al., 2018, grey and black profiles, Fig. 3d), our data (red profile, Fig. 3d) display lower noise amplitude and a clearer displacement signal across the fault zone. This highlights the gain using high-resolution (0.5 m) data to resolve complex displacement patterns. In the fault-parallel component, our results show that left-lateral displacement is mainly

accommodated by faults P1 and S1 that run alongside each other, for a total offset of 6 m. Another ~2 m are accommodated by faults S4 and S5 (~1 m each), in addition to some OFD within the relay and NW of the relay (red arrows, Fig. 3d). Because we have corrected the displacement maps for long wavelength artifacts using lower resolution displacement maps (see Methodology), we can measure and describe with confidence these gradients as OFD gradients. Shortening associated with the push-up relay zone is accommodated by faults P1 (2.3 m across profile BB', Fig. 3d) and S1 (0.9 m across profile BB', Fig. 3d). Associated extrados-extension occurs through extension on S5 and distributed OFD in the hanging-wall and the push-up area (green arrows, Fig. 3d). Uplift is localized principally on faults P1 and S1 but is also distributed across the entire push-up and in the hanging-wall (blue arrows, Fig. 3d).

Figure 3: (a) Sketch of the surface rupture overlapped on a 0.5 m resolution post-earthquake hillshade DSM. Primary faults are in red. (c) Map of fault orientations in the C2 complexity: red when following the primary fault orientation, light blue for ENE-WSW orientations, and dark blue for NNE-SSW orientations. Background surface rupture is from Vallage et al. (2015). (e) Azimuth distribution for the different faults shown in (b). (d) BB' profile for the three components. OFD gradients are highlighted with arrows. Black and grey profiles in the fault-parallel component were respectively taken from 2.5 m displacement maps of Zhou et al. (2018) and Vallage et al. (2015). (e-g) Displacement maps for a 3-km long section of the C2 complexity (see b). Surface rupture map in (g) is from Vallage et al. (2015). In (e): red right-angles between S4, S6 and S7 highlight ~90° azimuthal variations; dashed arrows overlapped on P1, S1, and S4 highlight gradual azimuthal variations

that show an east-west trend. (h) Norm of maximum shear strain, (i) curl, and (j) dilatation maps at 2.5-m ground resolution with profiles that cross P1, S1, and S4. The deformation signal on S1 and S4 does not come out from the noise in the profiles.

Within the C2 complexity, faults P1, S4 display a gradual evolution of their azimuth, in the ENE-WSW direction, when moving south-westwards (light-blue arrows in Fig. 3b, and dashed arrows in Fig. 3e), and meet up with secondary faults S5, S6, and S7 that bound the hanging-wall to the SW. Quite differently, fault S1 also align toward a ENE-WSW azimuth in its SW part; however, it rather connects down to fault P1 (blue arrow, Fig. 3c). S1 differs from the other faults since it does not generate a continuous displacement offset in the displacement maps (Fig. 3e,g). Similarly, it did not generate a clear shear, dilatation, or rotational signal, especially on its SW part (SW of profile GG'; Fig. 3h,j). This suggests that fault displacement along S1 did not entirely reach the surface on the western side. In addition, we observe similarities with displacement patterns across the C1 complexity. First, between S1 and P1, we observe heterogeneous displacement patterns associated with enhanced extension and local subsidence (relatively to the rest of the push-up). Second, we observe that P1 propagates farther SE of the mountain foot, suggesting a shallower dip angle of P1 in this region. Hence, deformation process acting in the area of S1 are likely similar to those described for the C1 complexity (Fig. 2 and Vallage et al., 2015).

3.2. Displacement profiles displayed in 3D

To better visualize the along-strike variations in the slip distribution and OFD gradients across the complexities, we display cross-fault displacement profiles in 3D. The plots

present the distribution of the fault-parallel component, corresponding to the main component of displacement for this event, across complexities C1 and C2 (Fig. 4). Similar plot for the fault-normal displacement component across C2 can be found in Figure S3.

Figure 4: Fault-parallel displacement profiles arranged in a 3D view for (a) the northern tip of the C1 complexity, (b) the C2 relay zone and, (c) zoom on the secondary fault S1 inside of C2 (Fig. 3e-j). See Figure 1b for the location of (a) and (b) in the displacement maps. Each profile corresponds to the stack of individual slip profiles over a width of 250 m for (a) and (b), and 100 m for (c). The slip on each fault is represented by the colored area, either in dark pink for the two primary faults (P1 and P2) or in light pink for the secondary faults (S1-7). Black arrows highlighting offsets along faults S4, S6, and S7 indicate the change between sinistral and dextral slip. Thick blue lines highlight few examples of OFD gradients. Dashed blue line in (c) marks the limit between the OFD zone of C1 and the hanging-wall. Subvertical red bars indicate localized deformation on small fractures within the OFD zone.

3.2.1. C1 complexity

The 3D plot across the C1 (Fig. 4a) illustrates the along-strike distribution of surface slip at the northern tip of the complexity, before the secondary fault observed in Figure 2a becomes visible. In this region, surface displacement distributes over a maximum width of ~300 m NW of P1. As slip on primary fault P1 decreases, from 12 m to the NE to 7.5 m to the SW, the distributed deformation zone gets wider and accounts for a larger part of the displacement budget. OFD gradients are steep and mark a clear transition with the

far-field slope. These gradients are irregular and display slope changes, with offsets of amplitudes ~0.10 to 2 m that reveal the presence of distributed fractures in the OFD zone. These fractures are ill-organized and distributed, sometimes organized as clusters, and present a length from <50 to 500 m. As a consequence, OFD patterns within C1 are highly heterogeneous in space.

3.2.2. C2 complexity

The 3D plot across the C2 relay zone (Fig. 4b) extends from the small extensional area to the north (S2-P1, 1.5 m of subsidence in Figure 1d) to the connection with the primary fault P2 to the SW. To the north of the relay zone, slip profiles are simple with one offset of 9.5 m on the primary fault P1 and some OFD for ~1 km in the hanging-wall. Across S1 (Fig. 4c), as presented using Figure 3e-j, displacement gradients are heterogeneous, and resemble those described along the C1 complexity (Fig. 4a). West of fault S1, we document an opposite sense of motion on fault S6, compared to faults S4 and S7. Offset on fault S6 is dextral, while offsets on faults S4 and S7 are sinistral. This can also be seen in the curl map from Figure 3i where the fault appears in yellow. Such inversion is due to the orientation of S6, perpendicular to faults S4 and S7, which makes dextral slip possible. This area constitutes a major transition in C2, where slip on primary fault P1 drops drastically to stabilize around 2 m whereas slip on faults S4 and S5 increases sharply (Fig. 4b). Faults S4 and S5 accommodate two thirds of the slip budget for 800 m before they merge into the primary fault P2, marking the end of the push-up. After this point, P2 becomes the major fault of the system and accommodates 7.5 m of displacement. It is important to notice that, overall, the amount of fault displacement after

the relay zone (7.5 m on P2 plus 2 m on P1) meets with the amount of fault displacement accommodated on P1 before the relay zone (9.5 m).

OFD gradients are also measured in the hanging-wall of the relay zone and between faults S4 and S5, up to 1.5 km away from the faults (Fig. 4b). Displacement gradients in these regions indicate a similar sense of motion as the faults (Fig. 4b), meaning that displacement is accommodated in the off-fault domain through OFD. However, these gradients differ from the steep-angle gradients measured across C1 and S1 (Fig. 4b). They correspond to a slight change in slope and do not mark a clear transition with neighboring areas where no OFD occurred. Also, in these regions, no cracks were mapped in the optical images (Vallage et al., 2015; rupture map Fig. 1d), nor were localized displacement offsets detected in our displacement maps (Fig. 1b-d). This means that OFD in and around the C2 relay zone affects the medium rocks in a homogeneous manner, without localization of the deformation, conversely to that in the C1 complexity. We cannot exclude that cracks smaller than the resolution of the dataset (0.5 m), and/or that accommodated displacements lower than our detection threshold (0.1 m), are included within the OFD gradients.

3.3. Quantification of the total displacement, fault displacements, and OFD

In this section, we used 100 m-spaced profiles (315 in total) across the fault zone to compute a budget of the coseismic deformation that documents the total surface displacement, the fault displacements, and the OFD (Fig. 5, and Fig. S4 for comparison with published data). The OFD budget is derived from the difference between the total displacement budget, which includes fault slip and OFD, and the sum of the

displacements measured on all the faults. Similar to the previous section that described displacement profiles in 3D, here we focus on the fault-parallel component of displacement. Also, because our measurements only address the near-fault deformation zone (4-5 km-wide), we use results from Vallage et al. (2015) at 2.5 m resolution to complement our data for the far-field area and trace ~9 km-long profiles (Figs. 5a, and S1). Doing so, we ensure that the far-field trend is well constrained. For each profile, we estimate the total displacement by using the step between linear regressions of the displacement gradients in the footwall and hanging-wall, far from the faults (thick black dashed lines in Fig. 5a). To quantify specific slip that is localized on the different faults of the system, we use shorter displacement profiles of a limited length of a few hundreds of meters. In this case, linear regressions are taken close (<100 m) to the offset to avoid incorporating OFD in the measurement. Uncertainties for the total and fault displacement measurements are expressed by the sum of the standard deviations (σ) of the two linear regressions in the hanging-wall and footwall. It ranges from 0.05 to 0.20 m depending on the profiles. Maximum standard deviations for the measurement of the total and fault displacements are respectively 0.066 and 0.171 m. Average standard deviation is 0.020 m for the total displacement curve, and 0.018 m for the fault displacement curves. Because sensor and topography artifacts can affect the tectonic signal across the fault, we conservatively assess that the maximum uncertainty associated with the measurement of the surface displacements is 0.20 m. To this is added the human bias related to the choice of the regions where linear regressions are taken outside of the fault zone. Human bias is unlikely to generate a large bias in this study because (i) linear regressions far from the fault are taken along portions of linear displacement gradients, and thus, a modification in the position of the points used to estimate the regression has no strong impact on the

slope of the regression, and (ii) linear regressions taken on the displacement offset itself and thus, are not impacted by the potential OFD gradients around.

Figure 5: (a) Fault parallel stacked slip profile showing 0.5 m-resolution results from this study, merged with 2.5 m-resolution results from Vallage et al. (2015) where 0.5 m-resolution results are not available. The stack is 100 m-wide. Central section of this profile, highlighted with a dashed horizontal line at the top of the figure, corresponds to profile BB' from Figure 3d. Thick dashed black lines correspond to linear regressions in the hanging-wall and footwall, outside of the fault zone. Fault displacement offsets are reported horizontally with red dashed lines and a vertical red arrow. Blue curves highlight OFD gradients. Blue and red lines along the x-axis report the width of OFD gradients and fault displacement offsets, respectively. (b) Surface rupture map from Vallage et al. (2015) with colors corresponding to the classification of the faults used for the slip budget in (c). Dashed grey lines above the two complexities correspond to the extent of OFD gradients (when wider than 200 m) in the hanging-wall of the ruptures (e.g., thick blue lines in Fig. 4a). (c) Fault parallel displacement budget along our study area. Black curve corresponds to the total displacement budget. Dashed grey line corresponds to the total slip budget approximated by a first-degree polynomial. Colored curves correspond to slip budget for individual faults with the same color code. Grey curve is the sum of fault slip contributions. Grey area is the OFD budget, i.e., the difference between the total displacement budget and the sum of fault slip contributions. Maximum uncertainty in the quantification of total and fault displacements is ± 20 cm.

The resulting displacement budget (Fig. 5b,c) shows a total displacement that decreases almost linearly along the study area, from 12 m NE to 9 m to the SW (dashed grey line; Fig. 5c). Smaller-wavelength variations include a sharp 1 m amplitude decrease in displacement at the north-east corner of C2 (14.5 km), a 2-m increase within the C2 area (16-19 km), and a sharp 2-m decrease at the south-western end of the C2 area (22-23 km) before it meets up again with the linear decreasing trend at 23 km. In regions where the fault zone consists solely in a localized and linear primary fault (0-2 km, 8.5-12.5 km, and 23-25 km; Fig. 5b,c), the total displacement is equivalent to displacements on the primary faults (red curve for P1, blue curve for P2, Fig. 5c). Conversely, across C1 and C2, displacements decrease on faults P1 and P2 and are accommodated by the secondary faults and the OFD zone. Both across C1 and C2, the large-scale OFD zone (>200 m) developed within the hanging-wall of the rupture, NW of the primary faults. Indeed, as visible in Figure 4, displacement profiles in the footwall of the ruptures (SE of P1 and P2) are horizontal and not affected by OFD gradients. This is explained by the fact that deformation at depth occurs along a NW dipping fault plane (Lauer et al., 2020).

Fault displacement curves present along-strike variability that is decorrelated from the total displacement budget evolution. They present, first, kilometer-scale variations correlated with modifications in the rupture geometry, as for example, the decrease in fault displacement observed in the C1 and C2 complexities. Second, they present a variability at the scale of hundreds of meters, sometimes from one profile to the following one, which is essentially observed in regions where fault traces are discontinuous (faults S1, S3, and S4) and/or where distributed fractures are observed in the off-fault medium (C1, P1 NE of C2, tip of P1, SW of P2). Indeed, these variations are not encountered in

the total displacement budget that remains stable along the strike of the rupture. This means that OFD, which corresponds to the difference between fault displacements and total displacement, entirely accommodates the variations in fault displacements, and acts as a buffer to maintain the total surface displacements budget stable even across major geometrical complexities. Along both the C1 and C2 complexities, OFD accommodates up to 70% of the surface displacements, with an average of 30% across both complexities. On average, along the area of study, 16% of the surface displacements are accommodated by OFD, and the other 84% are accommodated by the primary and secondary faults.

Comparison with the results from Zinke et al. (2014) and Gold et al. (2015) show that our total displacement budget is generally larger because our measurements include sub-parallel fault strands and km-scale OFD. Because we estimated offsets in the displacement maps with a 5-200 m aperture, slip curves from our study provide a maximum envelope of fault displacements compared to Zinke et al. (2014) and Gold et al. (2015) with a dense and continuous sampling. In fact, in Zinke et al. (2014) and Gold et al. (2015), the dispersion in offset amplitudes and clustering of the measurements along the rupture strike reflect the heterogeneity of the deformation markers mapped in the optical images. Hence, our approach allows us to refine the surface displacement budget and provide a finer measurement of OFD for our study area (Fig. 5c).

4. Discussion

4.1. Two different mechanisms for OFD

In this study, we document gradients of OFD with different amplitudes, ~ 10 m/km (Fig. 4a) and ~ 1 m/km (Figs. 3d, 4b, and 5a), occurring respectively in the C1 and C2

complexities. OFD gradients of amplitude ~ 10 m/km are associated with extension (Figs. 1c, 2b,f,g, and S3), and distributed fracturing of the off-fault medium (Figs. 1d and 2c). The fractures have a length of about a few tens to hundreds of meters, and could be mapped directly on optical images (Figs. 1d, and 2c; Gold et al., 2015; Vallage et al., 2015; Zinke et al., 2014). Such extension of the surficial crustal material in the first hundreds of meters of the hanging-wall occurs as a response to a change in the shallow dip angle of the primary fault (Vallage et al., 2015). Because the fractures are detectable directly on the optical images, this OFD could also be measured from direct photo-interpretation (Gold et al., 2015; Zinke et al., 2014). This explains the good correspondence between the total displacements measured in this study, and that measured by Zinke et al. (2014) and Gold et al. (2015) (Fig. S4).

However, OFD gradients of amplitude ~ 1 m/km, which were evidenced essentially in the C2 complexity, represent a greater challenge for the quantification of the total surface displacements. Indeed, these gradients have a wide (> 1 km) extension (Figs. 3d, 4b, and 5a), and are not characterized by visible fractures at the surface (Figs. 1d and 3b). Hence, they are difficult to detect based on field and photo-interpretation approaches. The lack of localized markers at the surface expresses the fact that this OFD affects the rocks at a scale below the image resolution (0.5 m). Also, the fact that the gradients are continuous and have a curvilinear profile (concave or convex depending on the side of the rupture) implies that the deformation homogeneously affects the volume of rocks. Hence, it brings into play mechanisms that do not localize the deformation on discrete fractures. A possibility to explain such a pattern, which has been observed in laboratory experiments, is the microfracturing of the rocks below the nominated failure stress. By measuring

acoustic emissions in rock deformation experiments, it was established that modifications of stress below 90-95% of the failure stress can trigger diffuse microfracturing of the rocks (Lockner et al., 1991; McBeck et al., 2022; Scholz, 1968). It is possible that millimeter-size to centimeter-size fractures are included within the OFD gradients, although their displacement remains below our detection threshold (~10 cm). Because diffuse microfracturing requires lower stresses than localized faulting, it can affect the medium over wider areas than brittle damage, and can explain why OFD is observed up to 1.5 km from the faults (Fig. 5b). For these reasons, such km-scale OFD gradients will be referred to as diffuse deformation.

Ultimately, at the C1 and C2 complexities, the rupture cuts through sandstones and shales that constitute the basement rocks of the Makran range (Bakr., 1964). Hence, the development of deformation bands (areas of modified rock porosity and grain reorganization; Fossen et al., 2007), and clay smears (slip surfaces in rocks that have >40% of phyllosilicate content; Fossen et al., 2007; Hamiel et al., 2004) is also possible, in complement of the diffuse deformation and distributed fracturing.

4.2. Control of the cross-fault width and cumulative deformation on OFD patterns

The fact that diffuse deformation and distributed fracturing are observed at geometrical complexities that widely differ in their geometry suggests a control of the rupture geometry on the OFD mechanisms. However, the fact that both complexities accommodate similar proportions of OFD, that is on average 30 % with local maxima up to 70 %, suggests that there is no direct relation between the rupture geometrical

complexity and the proportions of OFD regarding to the total surface displacement. Rather, the map of the spatial extent of OFD around the complexities (Fig. 5b) suggests that the extent of the OFD zone scales with the size of each complexity. As a consequence, we first propose that the cross-fault width of the complexity is the primary-controlling parameter of the OFD process. Second, we advance that this cross-fault width increases with increasing cumulative deformation across the complexity, also suggesting that the mechanisms of OFD evolve with increasing cumulative deformation across the fault system (Figs. 2 and 3).

On one hand, the C2 complexity has a ~2 km-wide surface extension (Fig. 1b-d). Because the faults on both sides of the relay zone accommodate opposite fault-normal displacements, although they accommodate positive vertical displacement, we interpret the relay zone as a positive flower-structure constituted of splay faults that face each other and join at depth. Also, as it is generally observed in analog modeling experiments (Dooley and Schreurs, 2012; Le Guerroué and Cobbold, 2006; McClay and Bonora, 2001), the depth extent of such flower structure is about equivalent to the width of the complexity at the surface. Hence, we propose C2 to be about 2 km-deep. Moreover, estimates of fault dip angle based on the inversion of geodetic data, outside of the C2 complexity, predict that fault P2 has a shallower dip angle than fault P1, and that the two faults may never directly connect at depth (Lauer et al., 2020). Added to the fact that secondary faults in C2 are well-localized, it shows that C2 is a long-lasting structure that affects the rupture geometry at regional scale, and accommodated displacements comparable to that of the entire fault system.

In contrast, the C1 complexity constitutes a narrower, <500 m-wide complexity that occurs within the trace of the primary fault P1 (Fig. 1b-d). From the fault-normal and vertical displacements observed along P1, we estimate a dip angle of P1 at the surface around 38° towards the N (fault dip angle is the arctan of vertical displacement over fault-normal displacement). This value is indeed shallower than the $55\text{-}60^\circ$ proposed for larger depth by other studies based on far-field data (Lauer et al., 2020; Zhou et al., 2015), although in good agreement with the conceptual model of dip change proposed by Vallage et al. (2015). Moreover, the ~ 500 m-long secondary fault limiting C1 to the NW accommodated only fault-parallel deformation (Fig. 2a-f), hence it is likely to have a vertical geometry. This would lead to a junction between P1 and the secondary fault around 275 m below the surface. This shows that C1 is a small complexity likely cutting only through the recent and superficial alluviums (Vallage et al., 2015). Added to the fact that ruptures across C1 are discontinuous and present small-scale (<200 m) changes in azimuth (Fig. 2a-f), it suggests that C1 is more recent complexity than C2. Consequently, it likely affects only superficially the rupture pattern.

The fact that rupture complexity is encountered at larger depth in the case of C2 favors the distribution of the deformation over a larger volume of rocks than for C1. Consequently, C2 widely distributes the strain around the faults and triggers diffuse deformation, whereas C1 concentrates the strain within a smaller region, and generates OFD on discrete fractures. In addition, a similar high-resolution characterization of the displacement field made along for the purely strike-slip 2019 Ridgecrest ruptures, California (Antoine et al., 2021), did not highlight such distributed fracturing. Hence, distributed fracturing of the off-fault medium such as it is observed across C1 (Fig. 2) and

S1 (Fig. 3) is likely triggered by the dip-slip components of the 2013 Baluchistan rupture, that is enhanced in these regions where the faults have shallow dip angles.

After that the complexity reached its maximum size that is controlled by the distance between the two primary faults (*e.g.*, Dooley and Schreurs, 2012), we propose that the deformation tends to localize on continuous structures through the development of new through-going faults across the complexity. Indeed, we observe that the S1 fault zone, that locates within the push-up area of C2, displays the characteristics of a newly developing fault, including discontinuity and roughness (Brodsky et al., 2011; Manighetti et al., 2021; Wesnousky, 1988) compared to the other secondary faults that are well-localized. Hence, we propose that S1 developed at a later stage of deformation to cross-cut the geometrical complexity of the fault system between P1, S6, and S7 (Fig. 3b,e). We hypothesize that, with increasing cumulative deformation, S1 would localize and constitute a continuous fault linking P1 to S4, and decreasing the level of complexity of the C2 relay zone. Then, the fault system would locally evolve toward a simpler configuration, with fault complexity that is likely displaced further away along the fault plane (Klinger 2010).

4.3. Partitioning of OFD

We evidence a partitioning of the OFD in the C1 complexity, with the fault-perpendicular OFD zone that is twice larger than the fault-parallel OFD zone (Fig. 2g). Across C1, the fault-parallel OFD zone is controlled by the lateral geometry of the rupture, whereas the fault-perpendicular OFD zone is controlled by the along-dip rupture geometry. Partitioning is generally described as the separation between components of fault slip that

are then accommodated on separate faults (King, 2005; Klinger et al., 2005). Partitioning of the deformation between the on- and the off-fault components has also been described (Vallage et al., 2014). For example, along the Denali (Alaska) fault system, it was evidenced that compressional aftershocks and microseismicity affect wider areas where fault obliquity is greater, and fault-parallel slip is lower (Vallage et al., 2014). Our analysis shows that partitioning also occurs within the OFD domain, with fault-parallel and fault-perpendicular OFDs that are accommodated through different mechanisms and affect regions of various width. Across C1, even if the fault-parallel OFD is accommodated essentially through distributed fracturing within the first 500 m around the primary fault (Fig. 1b,d), fault-normal OFD is distributed between these same fractures, and km-scale gradients of OFD (Figs. 1c,d and 2b). These OFD gradients differ from the diffuse deformation gradients described across C2 in the fact that they present changes in slope, with sections that are constant and sections of amplitudes about 10 m/km (Fig. 2b). This suggests that the evolution of the fault dip angle at depth is not linear and might presents several kinks. Fractures and subsidence are then encountered where the fault-normal OFD gradients are greater, which is likely above regions of greatest changes in fault dip angle.

4.4. Implications for the earthquake barrier model

In this study, we document a decrease in fault-parallel displacements across the fault geometrical complexities compared to the surrounding areas where the fault zone is localized (Fig. 5b,c). This decrease resembles what was previously evidenced for other earthquake ruptures, along their entire length, with smaller-amplitude fault displacements across perturbations in the rupture geometry (*e.g.*, Elliott et al., 2009; Fletcher et al., 2014;

Milliner et al., 2016b). As a consequence, these geometrical complexities are generally considered as barriers to slip propagation, and potential stopping points for the ruptures (King and Nabelek, 1985; Klinger, 2010; Schwartz and Coppersmith, 1984). In a few cases, fault-parallel slip decrease was shown to correlate with greater rock damage (Manighetti et al., 2004, 2005), or a fault-normal displacement increase (Klinger et al., 2006). In this study, we document wide (0.2-1.5 km) zones of fault-parallel OFD along the geometrical complexities that compensate for the decrease in fault-parallel slip, and allow for the total fault-parallel displacement budget to remain stable (Figs. 5c; 6). This suggests that the rupture energy budget is not impacted by the fault geometrical complexity, even though the latter was shown to affect the dynamic propagation of the rupture (Bruhat et al., 2020; Duan and Oglesby, 2005; Vallée et al., 2008).

Diffuse deformation has a predominant role in accommodating this decrease in fault displacements across geometrical complexities. The fact that diffuse deformation remains challenging to detect; and so widely undocumented, explains the apparent decrease in surface deformation generally reported across fault geometrical complexities (Choi et al., 2018; Klinger et al., 2006). However, diffuse deformation was encountered only at the C2 complexity and not at the C1 complexity, highlighting that complexities of varying cross-fault widths impact the rupture process differently. Indeed, diffuse deformation at C2 was explained by the fact that it is a wide (Fig. 1b-d) and long-lasting complexity that deeply (> km) affects the rupture process. C2 is located at the transition between two primary faults of the rupture (Fig. 1b-d), and it constitutes the transition between two rupture segments at the crustal scale (Klinger 2010). Conversely, C1 is a <0.5 km-wide superficial perturbation of the fault geometry, occurring within a single rupture segment.

Indeed, based on the geometrical analysis of the rupture trace (Klinger 2010), it was shown that the length of the fault segments that ruptured during the 2013 Baluchistan event is ~14 km (Lauer et al., 2020). This length is controlled by the width of the seismogenic zone (Jiao et al., 2021; Klinger, 2010; Lefevre et al., 2020), that is ~15 km in kinematic slip inversions (maximum depth of the slip patch; Jolivet et al., 2014; Lauer et al., 2020). Hence, because C1 occurs only a few kilometers NE of C2, it cannot represent an inter-segment complexity. Consequently, diffuse deformation likely occurs only at inter-segment complexities that deeply affect the rupture propagation, such as C2 (Fig. 6).

Figure 6: Idealized surface displacement distribution for a 3-segment rupture, as a function of rupture strike. Total surface displacement is in black. Fault displacement is in yellow. Diffuse deformation is in blue. In this scenario, diffuse deformation occurs both at inter-segment complexities (e.g., C2), and at rupture tips (Antoine et al., 2021; Han et al., 2021). Inter-segment geometrical complexities, similar to C2, are reported with red circles on the x-axis. Intra-segment geometrical complexities, similar to C1, and where no diffuse deformation occurs, are indicated with green circles on the x-axis. Earthquake epicenter location is set free in this model but most likely occurs at the red points (King and Nabelek, 1985).

5. Conclusions

In this paper, using 3D high-resolution (0.5 m) optical image correlation, we describe the near-fault displacement and deformation patterns associated with a 30 km-long area of the 2013 Baluchistan rupture. We quantify the on-fault, off-fault, and total strike-slip

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displacements with a <20 cm accuracy. We show a direct relation between the geometrical complexity of the fault trace and the occurrence of OFD at large-scale (0.2-1 km). Despite the strong variations in the geometry of the rupture, the total surface displacement budget remains stable along the rupture, and those variations in fault displacements are compensated by OFD occurring from 0.2 to 1.5 km away from the faults. We show no difference in the amounts of OFD between the two fault complexities analyzed in this study, even so, there are significant differences in the size and lithology of the complexities. Still, we highlight differences in the mechanisms responsible for the OFD between the two complexities. OFD across the <0.5 km-wide complexity is dominated by extensional deformation, and distributed fracturing of low-cohesion rocks. In contrast, OFD across the >2 km-wide complexity corresponds to diffuse microfracturing of the basement rocks below the failure stress. This analysis allows us to propose an idealized scenario of earthquake rupture that highlights the role of diffuse deformation in the rupture pattern, and to categorizes the complexities into two different types: inter-segment complexities that can act as potential barriers to rupture propagation, and intra-segment complexities that only affect the shallow rupture pattern. This work emphasizes new deformation processes that occur over wide areas around active faults, and that are undetectable in the field for most part. These processes need to be further taken into account when assessing the deformation budget of an earthquake.

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Open research

The Pleiades images were provided by the CEOS Seismic Hazards Pilot from ESA (<http://ceos.org/ourwork/workinggroups/disasters/earthquakes>) and the ISIS program from CNES (<https://dinamis.data-terra.org>), and are covered by an Institutional User Licence. The WorldView images (©2019, DigitalGlobe/Maxar) were accessed via the NextView licensing agreement, and can be found at <https://imagehunter.apollomapping.com> by selecting a date and search area. MicMac correlation software can be accessed and downloaded at <https://github.com/micmacIGN>. Supplementary figures providing details on the methodology and on the results of this study are available in the electronic Supplementary Materials. Surface displacement maps at 1 m ground resolution are available at: S.L. Antoine, Y. Klinger, A. Delorme, and R. D. Gold (2022), “East-west, north-south and vertical displacement maps for the 2013 Baluchistan earthquake (Pakistan) at 1 m ground resolution.”, Mendeley Data, v2, DOI: 10.17632/hv762x5dkz.2, <https://data.mendeley.com/datasets/hv762x5dkz/2>.

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