Large Surface-Rupture Gaps and Low Surface Fault Slip of the 2021 M$_w$ 7.4 Maduo Earthquake Along a Low-Activity Strike-Slip Fault, Tibetan Plateau

Zhao de Yuan$^1$, Tao Li$^{1,2}$, Peng Su$^1$, Haoyue Sun$^1$, Guanghao Ha$^1$, Peng Guo$^1$, Guihua Chen$^1$, and Jessica Thompson Jobe$^3$

$^1$State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing, China, $^2$Lhasa National Geophysical Observation and Research Station, Institute of Geology, China Earthquake Administration, Beijing, China, $^3$U.S. Geological Survey, Geologic Hazards Science Center, Golden, CO, USA

Abstract Based on field investigations, interpretations of high-resolution UAV images, and analyses of available InSAR data, we mapped the fault geometry and surface ruptures of the 2021 M$_w$ 7.4 Maduo earthquake that occurred on a low-activity strike-slip fault within the Tibetan Plateau. The results indicate that (a) the earthquake activated a fault that is ∼161 km long and has complicated structural geometry; (b) the surface rupture occurs over a distance of 148 km, but is separated into three distinct segments by two large gaps (38 and 20 km, respectively); (c) within the surface-rupture segments, the horizontal and vertical displacements are typically 0.2–2.6 m (much lower than the InSAR-based slip maximum of 2–6 m at depth) and ≤0.4 m, respectively. The two large gaps of the Maduo surface rupture represent the two largest surface-rupture discontinuities of strike-slip earthquakes ever documented, and coincide with structurally complicated fault portions and near-surface soft sediments.

1. Introduction

Compared to major, high-activity strike-slip faults that have a high Quaternary slip rate and a large total slip, for example, the San Andreas Fault, the North Anatolian Fault, and the Altn Tagh Fault (Quaternary slip rate of ≥10 mm/a and total slip from 80 to >400 km; e.g., Armijo et al., 1999; Cowgill et al., 2003; Gold et al., 2009; Hubert-Ferrari et al., 2002; Weldon & Sieh, 1985; Wesnousky, 1988), secondary, low-activity strike-slip faults host the seismic potential that is substantially more challenging to evaluate. Such low-activity faults commonly have spatially distributed faulting deformation and subtle topographic expression and, therefore, are difficult to map; some fault segments could be identified only after an earthquake (e.g., the 2010 M$_w$ 7.2 El Mayor-Cucapah, Mexico event, the 2010 M$_w$ 7.1 Darfield, New Zealand event, and the 2019 M$_w$ 7.1 Ridgecrest, California event; Fletcher et al., 2014; Quigley et al., 2012; Xu et al., 2020). Moreover, limited fault slip at the surface (relative to that at depth) produced by each earthquake can make it easy to underestimate earthquake magnitude based on measurements of geomorphic offsets (e.g., the 1992 M$_w$ 7.3 Landers, California event and the 2019 M$_w$ 7.1 Ridgecrest, California event; Dolan & Haravitch, 2014; Gold et al., 2021; Milliner et al., 2015).

On 21 May 2021 (18:04 UTC), an M$_w$ 7.4 earthquake struck Maduo town within the Tibetan Plateau (Figure 1). Earthquake parameters from the U.S. Geological Survey (https://earthquake.usgs.gov/earthquakes/search/) and Global Centroid-Moment Tensor Project (https://www.globalcmt.org/) indicate an epicenter location near (34.6°N, 98.4°E), a focal depth of ~10 km, and a sinistral-slip-dominated mechanism. InSAR (Interferometric Synthetic Aperture Radar) data reveal that coseismic slip occurred at 0–15 km depth with maximum slip of 2–6 m at 0–7 km depth (e.g., Chen et al., 2021; He et al., 2022; Jin & Fialko, 2021; Xu et al., 2021). The Tibetan...
Plateau, which is formed in response to the ongoing India-Asia collision, has hosted numerous large strike-slip earthquakes (Figure 1), for example, the 1920 M 8.5 Haiyuan, the 1951 M 8.0 Dangxiang, the 1973 M 7.6 Luhuo, and the 2001 M 7.8 Kunlunshan events. Most of these earthquakes are concentrated along the major strike-slip faults, including the Haiyuan Fault, the Eastern Kunlun Fault, the Ganzi-Yushu-Xianshuihe fault system, and the Jiali fault system (e.g., Gan et al., 2007; Tapponnier & Molnar, 1977; Zhang et al., 2013). Comparatively, the 2021 Maduo event occurred on a secondary, low-activity strike-slip fault (named the Kunlunshankou–Jiangcuo Fault), which is one of eight subparallel left-lateral strike-slip faults that form a diffuse zone between the Eastern Kunlun Fault and the Ganzi-Yushu-Xianshuihe fault system (Li et al., 2021; Pan et al., 2021; Zhan et al., 2021). The fault has ambiguous topographic expression and has not been well mapped in previous studies (e.g., Deng et al., 2007; Xu et al., 2016); interseismic strain rate along it is determined to be in a low level as well (almost undetectable based on 2015–2020 InSAR data; Zhao et al., 2021).
Beginning 1 day after the earthquake, we conducted field work to investigate the earthquake-fault geometry and surface-rupture pattern. Using relocated aftershocks (Wang et al., 2021), InSAR data (e.g., Zhao et al., 2021), and pre-event Google Earth images, along with field observations, we identified and located the surface rupture. We then used UAV (unoccupied aerial vehicle) photography to obtain high-resolution (pixel = 4–8 cm) images that cover the entire rupture zone (the flight swath width of 1.0–8.5 km and the total area of ~520 km²; see Text S1 & Data set 1 in Supporting Information S1). Interpretations of these images, allowed us to accurately map the spatial extent, the full geometric complexity, and the displacement distribution of the surface rupture (see Text S1, Tables S1 and S2, and Datasets 2–4 in Supporting Information S1). Our results reveal that the 2021 Maduo surface rupture not only has low fault slip (relative to that at depth), but includes two large gaps that correlate with geometric fault complexities (showing discontinuous, obliquely aligned short sections). These results have implications that evaluating the seismic potential of low-activity strike-slip faults is probably more challenging than previously thought.

2. Earthquake Fault Geometry and Surface Rupture Geometry

The epicenter (Wang et al., 2021) and source modeling (https://earthquake.usgs.gov/earthquakes/search/) indicate that the earthquake rupture initiated near the Yellow River valley, then propagated 76 km to the west and 85 km to the east (Figure 2a). For ease of referencing observations along the earthquake rupture, we assign the epicenter as “0 km”, and project observations onto a simplified line paralleling the InSAR-based earthquake rupture toward the east and west. Along the earthquake rupture length, the surface rupture is generally characterized by a series of right-stepping en echelon tensional or transtensional cracks, sometimes in combination with mole tracks, showing a typical pattern of left-lateral slip (Figure 3). Besides the surface faulting rupture, numerous secondary cracks due to seismic shaking, which are typically subparallel with river valleys, lake shorelines, and/or topographic contours, were formed (Figure 2b and Dataset 2 in Supporting Information S1).

From the epicenter westward, the earthquake fault extends northwestward for 45 km and is dominantly localized within mountainous terrain or along the mountain-range front (Figure 2a). To the east of the Yematan Bridge (W29 km), the fault comprises an array of obliquely aligned short (2–8 km) sections that trend N65°W as an entire. Pre-event topographic expression (e.g., stream channel offsets and linear troughs) of the fault is unclear. Along the fault length, we identified abundant secondary cracks and liquefaction features along the Black River, but only 2-km-long surface rupture at its westernmost part (Figures 2b and 2c). West of the Yematan Bridge, the fault bends clockwise to N59°W and has a relatively linear geometry. The surface rupture is mostly a single continuous strand, although several small steps (few hundreds of meters) are observed.

At W45 km, the earthquake fault bends counterclockwise 17° to extend along a nearly west-trending obscure fault, rather than along its northwestward continuation that has more prominent topographic expression (Figure 2a). The associated surface rupture is relatively discontinuous and sinuous, with several bends, gaps, and branches (Figures 2b and 2c). From W60 km westward, the surface rupture splays into multiple parallel fault strands over a width of 400–700 m. We locate the western end of the surface rupture at W71 km near the southern edge of the Erling Lake, because no evidence of surface rupture can be identified farther west either in the field or on UAV images.

The earthquake fault east of the epicenter is separated from its western half by a 2–3 km releasing (left) step, where a pull-apart basin formed (Figure 2a). Within the basin, we mapped extensive fields of secondary cracks and liquefaction, particularly at the Yellow River valley (Figure 2b). However, no surface ruptures were confidently identified. From the epicenter eastward, the fault strikes N68°W for 19 km, bends counterclockwise to nearly east-trending for 10 km, and then bends back to NW-trending for an additional 31 km. To the west of E37 km, the fault follows the long-lived, fault-controlled linear troughs within the mountainous terrain, displaying a relatively simple geometry (Figure 2a; Figure S3a). To the east of E37 km, the fault crosses swampy and mountainous terrain, and then enters sand-dune terrain, showing a succession of obliquely aligned short (2–4 km) sections. The surface rupture is dominantly localized within the mountainous terrain from E12 to E37 km (Figures 2b and 2c): It is punctuated by steps and gaps between E12 and E25 km; eastward from E25 km it becomes relatively simple and continuous, but splays into two strands at E32 km. The main (southern) strand breaks into multiple subparallel strands trending N66°W for 6 km. The northern strand, which trends at 13° to the
Figure 2.
main strand, can be traced for a length of 4.5 km. The surface rupture becomes highly discontinuous from E37 km and vanishes completely from E41 km eastward.

From E61 km eastward, the earthquake fault bends counterclockwise to cross mountainous terrain in a nearly E-W direction, then bends gradually to N79°E along a tributary valley of the Youerqu River (Figure 2a). Although paleoscarps and deflected stream channels can be identified along the fault length (Figure 2a; Figure S3b), the fault appears to be recently activated because of its oblique alignment with the NW-trending modern topographic reliefs controlled by Cenozoic structures. The surface rupture, including numerous small-scale bends and branches, is dominantly localized within the mountainous terrain between E61 and E74 km (Figures 2b and 2c).

To the east of the Youerqu River, an additional 3 km of surface rupture is mappable. We cannot find confident surface ruptures beyond east E77 km, indicating that the surface rupture stopped very close to this point. Approximately 4.5 km to the south, we also mapped a 5-km-long secondary rupture strand parallel to the main rupture strand. This secondary strand merges onto the main earthquake fault at E58 km, through a NW-trending, blind fault.

Overall, the Maduo earthquake activated a complicated fault system that exhibits significant along-strike variation of structural geometry (Figure 2a). The surface rupture along the fault length can be identified over a distance of 148 km from W71 to E77 km (Figures 2b and 2c), within which, however, a 38 km gap from W26 to E12 km and a 20 km gap from E41 to E61 km are mapped. These two large gaps separate the surface rupture into three distinct segments.

3. Surface Displacement Distribution

Based on measurements both in the field and on high-resolution UAV images (and DEM), we collected totally 125 horizontal and 169 vertical displacements to characterize surface slip distribution of the 2021 Maduo earthquake (Figure 2c; see Text S1, Tables S1 and S2 and Datasets 3 and 4 in Supporting Information S1). Along the western surface-rupture segment, the horizontal displacement is expressed as two peaks of high displacements separated by low displacements around the 17° fault bend (W45 km). To the west and east of the fault bend, the displacement typically ranges from 0.2 to 2.6 m and from 0.2 to 1.8 m, respectively. The 2.6 ± 0.3 m at W58 km represents the maximum horizontal displacement we have measured. In comparison, along either the middle or the eastern surface-rupture segment, displacement decreases from its central portion toward either end. Displacement is 0.2–1.3 m and 0.2–2.4 m, respectively. Additionally, seven measurements yield displacements of 0.3–0.7 m along the secondary branch of the eastern surface-rupture segment.

It is noted that the offsets at three sites (Y13, g33, and G017) were measured by Pan et al. (2021) and/or Gai et al. (2021) as well. At Y13 (Figure 3c), our measured 1.40 ± 0.14 m of the tire track offset is much lower than the measured 2.9 m of Pan et al. (2021). This discrepancy is because our measurement was localized on the offset of tire tracks at two sides of the rupture trace, which yields a minimum value; while Pan et al. (2021) projected trend lines of tire tracks on the rupture trace and measured the distance of the trend lines (Figure 3c). Considering that the shape of tire tracks appears to be curved prior to the earthquake, the measurement of Pan et al. (2021) would significantly overestimate the displacement. Therefore, in this study, we prefer to use the minimum value of 1.40 ± 0.14 m, but rank it into intermediate reliability (see Table S1 and Data set 3 in Supporting Information S1). At other two sites, our measurements (1.4 ± 0.2 m at g33 and 1.1 ± 0.1 m at G017) are generally consistent with those (1.1–1.8 m at g33 and 1.1 m at G017) of Pan et al. (2021) and Gai et al. (2021).

Vertical displacements are generally small along the Maduo surface rupture (Figure 2c): They are typically ≤0.4 m and 112 of our measurements are close to zero. The only exception is the segment between W35 and W38 km, where vertical displacements are >0.5 m (>40% of the horizontal displacement), indicating significant dip slip component. Additionally, both the western surface-rupture segment from W29 to W45 km and the middle

Figure 2. (a) The 2021 Maduo earthquake fault interpreted from InSAR data (see Text S1 in Supporting Information S1) and its correlation with regional active faults (from interpretation of Google Earth images; long-lived linear troughs and paleoscarps shown in Figure S3) and Cenozoic faults (from published 1:200,000 geologic maps). (b) Surface rupture and secondary cracks (details shown in Data set 2 in Supporting Information S1) produced by the Maduo earthquake overlain on a simplified geologic map highlighting Quaternary sedimentary units (from interpretation of Google Earth images). The pre-Cenozoic bedrock (mountainous terrain), dominated by quartz sandstone and slate of the Triassic, has relatively homogeneous lithology. (c) Horizontal and vertical displacement distribution (with high, intermediate, and low reliabilities; details shown in Tables S1 and S2 and Datasets 3–4 in Supporting Information S1) of the Maduo earthquake.
surface-rupture segment are dominantly north-side-up, while both the western surface-rupture segment from W45 to W71 km and the eastern surface-rupture segment are dominantly south-side-up. Such contrasting sense of vertical displacements suggests a change of fault slip sense (with normal vs with reverse component) or fault dip direction (south vs. north).

Figure 3. (a), (b) UAV photos showing right-stepping tensional cracks of the 2021 Maduo surface rupture (see Figure 2b for locations). (c) A UAV photo showing the tire track offset (Y13) measured both in Pan et al. (2021) and in this study. Our measurement (140 ± 14 cm) was localized on the offset of tire tracks at two sides of the rupture trace, while Pan et al. (2021) projected trend lines of the tire tracks on the rupture trace and measured the distance of two trend lines (d)–(f) Field photographs showing tensional or transtensional cracks (d) and mole tracks (e), (f) of the Maduo surface rupture (see Figures 2b and 3b for locations).
4. Discussions and Implications

Our field investigations and UAV photograph interpretations, along with analyses of available InSAR data, document several important observations of the 2021 Mw 7.4 Maduo earthquake. First, the earthquake occurred on a strike-slip fault that has subtle topographic expression and complicated structural geometry (Figure 2a). Prior to the earthquake, the active fault segment between W45 and E85 km could be identified or speculated based on, for example, stream channel offsets, linear troughs, and paleoscarps; however, the fault segment between W45 and W76 km appears to be impossibly identified even after the most careful geomorphic mapping. Second, our measured fault displacements typically range from 0.2 to 2.6 m, much lower than the InSAR-based slip maximum of 2–6 m at 0–7 km depth (e.g., Chen et al., 2021; He et al., 2022; Jin & Fialko, 2021; Xu et al., 2021). Taking InSAR results from He et al. (2022) and Jin and Fialko (2021) as examples (Figure 4), our measurements are 2.5–2.7 m (on average) lower than the InSAR-based slip maximum; the ratio between our measurements and the slip maximum is <15%. Such reduced fault displacements also have been observed in other Mw 7.0+ earthquakes (e.g., the 1992 Landers, 2010 El Mayor-Cucapah, 2010 Darfield and 2019 Ridgecrest events) that occurred on low-activity strike-slip faults, and can be explained by that (a) the fault slip did not totally propagate upward to the surface (named shallow-slip deficit; e.g., Fialko et al., 2005) and/or by that (b) the fault slip was distributed across a wide deformation zone and accommodated by off-fault deformation (e.g., Dolan & Haravitch, 2014; Gold et al., 2021; Milliner et al., 2015; Rockwell et al., 2002). For the Maduo earthquake, the coseismic slip pattern from InSAR data yields low shallow-slip deficit (Chen et al., 2021; He et al., 2022; Jin & Fialko, 2021; Xu et al., 2021): for example, in Jin and Fialko (2021) and He et al. (2022), the InSAR-based slip near the surface is 2.2–2.6 m (on average), accounting for 70%–90% of the slip maximum; the shallow-slip deficit is only 10%–30% (Figure 4). Because most of the fault displacement at depth has propagated upward to the near-surface, the reduced fault displacement of the Maduo earthquake can be dominantly ascribed to off-fault deformation. The magnitude of off-fault deformation cannot be determined in this study due to lack of long, linear cultural markers across the surface-rupture zone (Rockwell et al., 2002). In future work, a comparison of optical-pixel correlation of pre- and

![Figure 4.](image-url)
post-event satellite images with our geological measurements may provide some constraints on its magnitude (e.g., Gold et al., 2021; Milliner et al., 2015).

Another key observation in the Maduo earthquake is the two large gaps (38 and 20 km) within the 148 km surface rupture. Earthquake surface rupture of strike-slip faults commonly includes a certain number of geometric discontinuities, that is, gaps (absence of surface rupture along the strike of earthquake fault) and steps (orthogonal jump from one surface-rupture segment to the next; e.g., Barka & Kadinsky-Cade, 1988; Wesnousky, 2006). Such geometric discontinuities typically reflect the location where the fault plane is not well connected, and are expected to have a maximum size above which the earthquake rupture will not pass through. Based on statistics of 46 historical strike-slip earthquakes by Biasi and Wesnousky (2016), gaps and steps have a maximum size of 10 and 5 km, respectively. Several well-documented earthquakes in recent studies, for example, the 1905 M ≥ 8 Tsetserleg-Bulnay, Mongolia earthquake sequence (e.g., Choi et al., 2018), the 2001 Mw 7.8 Kunlunshan, Tibet event (e.g., Klinger et al., 2005; Xu et al., 2006), the 2010 Mw 7.1 Darfield, New Zealand event (e.g., Quigley et al., 2012), and the 2019 Ridgecrest, California earthquake sequence (e.g., DuRoss et al., 2020), have quite continuous surface rupture. The Maduo earthquake, therefore, has the two largest surface-rupture discontinuities of strike-slip earthquakes ever documented.

As illustrated in Figure 2a, the two large gaps are approximately correlated with fault segments that are characterized by obliquely aligned short sections and show more complicated geometry than other fault segments. Herein, both InSAR-based slip maximum at depth and slip near the surface have relatively low values as well (Figure 4). The formation of these two large gaps, therefore, can be ascribed to the complicated fault geometry; along geometrically complicated fault segments, fault slip is accommodated on a multitude of fault strands and spreads over a wide deformation zone, thereby likely producing on-fault slip deficits or even a slip gap (e.g., Dolan & Haravitch, 2014; Klinger et al., 2006; Milliner et al., 2015). It is also noted that the surface rupture from E61 to E74 km is relatively continuous within the mountainous terrain (Figure 2b), but vanishes abruptly as it extends westward into the sand-dune terrain (E52-E61 km). The 9 km gap from E52 to E61 km can be partially attributed to near-surface soft sediments, through which the coseismic slip will become more distributed and cannot produce clear fault surface rupture (e.g., Bray et al., 1994; McGill & Rubin, 1999; Milliner et al., 2015; Teran et al., 2015). For other portions of the earthquake fault, however, there is no spatial correlation between near-surface soft sediments and surface-rupture gaps or on-fault slip deficit (Figure 4). Overall, we suggest that the complicated fault geometry, and along with near-surface soft sediments, account for the formation of the two large surface-rupture gaps.

Compared to major strike-slip faults, low-activity, secondary strike-slip faults are more ubiquitous but have not been studied in the same level of detail. An earthquake analogous to the 2021 Maduo event generated by a low-activity fault may produce unexpectedly severe damage, particularly if the fault is proximal to urban population centers or important infrastructure. Identification of such seismic sources, however, appears to be highly challenging. This is not only due to (a) the difficulty in the causative fault geometry mapping and (b) the limited surface on-fault slip, but due to (c) the large dimension of surface-rupture gaps that may correlate with geometric fault complexity: Large surface-rupture gaps make it impossible to retrieve paleoearthquake history of the relevant fault segment based on geologic or geomorphic offsets; moreover, large gaps and related geometric complexities commonly bias researchers to interpret each surface-rupture segment as an individual seismic source, distorting estimates of total earthquake fault length and, hence, earthquake magnitude. To reliably predict or reconstruct the hazards posed by large, infrequent, and complex ruptures along low-activity strike-slip faults, therefore, more detailed surface mapping, geophysical exploration, and paleoseismic trenching work are required, and larger dimension (probably up to 40 km wide) of structural complexity indicated by surface-rupture discontinuity should be considered to be possibly passed through.

**Data Availability Statement**

Data for the manuscript is available via Yuan et al., 2022 (https://doi.org/10.5281/zenodo.5915150).
Acknowledgments

This study was funded by National Nonprofit Fundamental Research Grant of China, Institute of Geology, China Earthquake Administration (grant IGCEA2136, IGCEA2138), and by the Second Tibetan Plateau Scientific Expedition and Research Program (2019QZKK0901). We thank K. He and Z. Jin for sharing their InSAR results and D. Burbank, P. Zhang, J. Sun, L. Fang, D. Zhao, and W. Feng for fruitful discussions. This manuscript was improved significantly by thoughtful comments and suggestions from G. Fletcher, J. Teran, O. J., Rockwell, T. K., Oskin, M. E., Hudnut, K. W., Mueller, K. J., et al. (2014). Assembly of a large earthquake from a complex fault system: Surface rupture kinematics of the 4 April 2010 El Mayor-Cucapah (Mexico) Mx 7.2 earthquake. Geosphere, 10, 797–827. https://doi.org/10.1130/geo200933.1

References

Armijo, R., Meyer, B., Hubert, A., & Barka, A. (1999). Westward propagation of the north Anatolian Fault into the northern Aegean: Timing and kinematics. Geology, 27, 267–270. https://doi.org/10.1130/0091-7613(1999)027<0267:WPOTN5>2.3.co;2

Barka, A., & Kadinsky-Cade, K. (1988). Strike-slip fault geometry in Turkey and its influence on earthquake activity. Tectonics, 7, 663–684. https://doi.org/10.1029/TC007p00663

Biasi, G., & Wesnousky, S. (2016). Steps and gaps in ground ruptures: Empirical bounds on rupture propagation. Bulletin of the Seismological Society of America, 106, 1110–1124. https://doi.org/10.1785/0120150175

Bray, J., Seed, R., Cluff, L., & Seed, H. (1994). Earthquake fault rupture propagation through soil. Journal of Geotechnical Engineering, 120, 543–561. https://doi.org/10.1061/(ASCE)0733-9410(1994)120:5(543)

Chen, H., Qu, C., Zhao, D., Ma, C., & Shan, X. (2021). Rupture kinematics and coseismic slip model of the 2021 M7.3 Maduo (China) earthquake: Implications for the seismic hazard of the Kunlun Fault. Remote Sensing, 13, 3327. https://doi.org/10.3390/rs13163327

Choi, J., Klinger, Y., Ferry, M., Ritz, J., Kurtz, R., Rizza, M., et al. (2018). Geologic inheritance and earthquake rupture processes: The 1905 M ≥ 8 Tsetserleg-Bulnay strike-slip earthquake sequence. Mongolia. Journal of Geophysical Research: Solid Earth, 123, 1925–1953. https://doi.org/10.1002/2017jb013962

Cowgill, E., Yin, A., & Harrison, T. (2003). Reconstruction of the Altyn Tagh Fault based on U-Pb geochronology: Role of back thrusts, mantle sutures, and heterogeneous crustal strength in forming the Tibetan plateau. Journal of Geophysical Research, 108, 2346. https://doi.org/10.1029/2002jb002080

Deng, Q., Ran, Y., Yang, X., Min, W., & Chu, Q. (2007). Present-day crustal motion within the Tibetan Plateau inferred from GPS field measurements and optical image correlation results. Geophysical Research Letters, 34, L22309. https://doi.org/10.1029/2007GL030764

Fletcher, J., Teran, O. J., Rockwell, T. K., Oskin, M. E., Hudnut, K. W., Mueller, K. J., et al. (2014). Assembly of a large earthquake from a complex fault system: Surface rupture kinematics of the 4 April 2010 El Mayor-Cucapah (Mexico) Mx 7.2 earthquake. Geosphere, 10, 797–827. https://doi.org/10.1130/geo200933.1

Gai, H., Yao, S., Yang, L., Kang, T., Yin, X., Chen, T., & Li, X. (2021). Coseismic surface rupture characteristics, causes and significance of the “5-22” Ms 7.4 earthquake in Maduo, Qinghai. Journal of Geomechanics, 7(3). https://doi.org/10.1002/jgm.2706.03.073

Gan, W., Zhang, P., Shen, Z., Niu, Z., Wang, M., Wan, Y., et al. (2007). Present-day crustal motion within the Tibetan Plateau inferred from GPS measurements. Journal of Geophysical Research, 112, B08416. https://doi.org/10.1029/2006JB004120

Gold, R., Cowgill, E., Arrowsmith, J., Gosse, J., Chen, X., & Wang, X. (2009). Riser diachrony, lateral erosion, and uncertainty in rates of strike-slip faulting: A case study from tuzudun along the Altyn Tagh Fault, NW China. Journal of Geophysical Research, 114, B04401. https://doi.org/10.1029/2009JB006913

Fialko, Y., Sandwell, D., Simons, M., & Rosen, P. (2005). Three-dimensional deformation caused by the Bam, Iran, earthquake and the origin of shallow slip deficit. Nature, 435, 295–299. https://doi.org/10.1038/nature03425

Hubert-Ferrari, A., Armijo, R., King, G., Meyer, B., & Barka, A. (1999). Westward propagation of the north Anatolian Fault into the northern Aegean: Timing and kinematics. Geology, 27, 267–270. https://doi.org/10.1130/0091-7613(1999)027<0267:WPOTN5>2.3.co;2

Klinger, Y., Xu, X., Cao, Y., & Zhao, Y. (2022). Fault geometry and slip distribution of the 2021 M7.3 Maduo, China, earthquake inferred from InSAR measurements and relocated aftershocks. Seismological Research Letters, 93, 8–20. https://doi.org/10.1785/012020010204

Quigley, M., Van Dissen, R., Litchfield, N., Villamor, P., Duffy, B., Barrell, D., et al. (2012). Surface rupture during the 2010 Mw 7.1 Darfield (Canterbury) earthquake: Implications for fault rupture dynamics and seismic-hazard analysis. Geology, 40, 555–558. https://doi.org/10.1130/G33523.1

Milliner, C., Dolan, J., Hollingsworth, J., Leprince, S., Ajoubi, F., & Sammis, C. (2015). Quantifying near-field and off-fault deformation patterns of the 1992 M7.3 Landers earthquake. Geoscience, Geophysics, Geosystems, 16, 1577–1588. https://doi.org/10.1002/2014rg000693

Pan, J., Bui, M., Li, C., Liu, F., Li, H., Liu, D., et al. (2021). Coseismic surface rupture and seismogenic structure of the 2021-05-22 Maduo (Qinghai) Ms 7.4 earthquake. Acta Geologica Sinica, 95(6), 1655–1670.

Quigley, M., Van Dissen, R., Litchfield, N., Villamor, P., Duffy, B., Barrell, D., et al. (2012). Surface rupture during the 2010 Mw 7.1 Darfield (Canterbury) earthquake: Implications for fault rupture dynamics and seismic-hazard analysis. Geology, 40, 55–58. https://doi.org/10.1130/g33523.1

Rockwell, T. K., Lindvall, S., Dawson, T., Langridge, R., Lettis, W., & Klinger, Y. (2002). Lateral offsets on surveyed cultural features resulting from the 1999 Izmit and Duzce earthquakes, Turkey. Bulletin of the Seismological Society of America, 92, 79–94. https://doi.org/10.1785/0120000809

Teran, O., Fletcher, J., Oskin, M., Rockwell, T., Hudnut, K., Spelz, R., et al. (2015). Geologic and structural controls on rupture zone fabric: A field-based study of the 2010 Mw 7.2 El Mayor-Cucapah earthquake surface rupture. Geosphere, 11, 899–920. https://doi.org/10.1029/2014GC003781

Wang, W., Fang, L., Wu, J., Tu, H., Chen, L., Lai, G., & Zhang, L. (2021). Aftershock sequence relocation of the 2021 Mw 7.4 Maduo earthquake, Qinghai, China (in Chinese). Science China Earth Sciences, 51, 1193–1202. https://doi.org/10.1007/s11870-018-7153-7
Weldon, R., & Sieh, K. (1985). Holocene rate of slip and tentative recurrence interval for large earthquakes on the San Andreas Fault, Cajon Pass, southern California. *The Geological Society of America Bulletin*, 96, 793–812. https://doi.org/10.1130/0016-7606(1985)96<793:hrsati>2.0.co;2

Wesnousky, S. (1988). Seismological and structural evolution of strike-slip faults. *Science*, 335, 340–343. https://doi.org/10.1038/335340a0

Wesnousky, S. (2006). Predicting the endpoints of earthquake ruptures. *Nature*, 444, 358–360. https://doi.org/10.1038/nature05275

Xu, L., Chen, Q., Zhao, J., Liu, X., Xu, Q., & Yang, Y. (2021). An integrated approach for mapping three-dimensional coseismic displacement fields from Sentinel-1 TOPS data based on DInSAR, POT, MAI and BOI techniques: Application to the 2021 M\textsubscript{s} 7.4 Maduo earthquake. *Remote Sensing*, 13, 4847. https://doi.org/10.3390/rs13234847

Wesnousky, S. (1988). Seismological and structural evolution of strike-slip faults. *Science*, 335, 340–343. https://doi.org/10.1038/335340a0

Wesnousky, S. (2006). Predicting the endpoints of earthquake ruptures. *Nature*, 444, 358–360. https://doi.org/10.1038/nature05275

Xu, X., Han, Z., & Yang, X. (2016). *Seismotectonic map of China and adjacent areas* (in Chinese). Seismological Press.

Xu, X., Sandwell, D., Ward, L., Milliner, C., Smith-Konter, B., Fang, P., & Bock, Y. (2020). Surface deformation associated with fractures near the 2019 Ridgecrest earthquake sequence. *Science*, 370, 605–608. https://doi.org/10.1126/science.abc1690

Xu, X., Yu, G., Klinger, Y., Tapponnier, P., & Van der Woerd, J. (2006). Reevaluation of surface rupture parameters and faulting segmentation of the 2001 Kunlunshan earthquake (M\textsubscript{s} 7.8), northern Tibetan Plateau, China. *Journal of Geophysical Research*, 111, B05316. https://doi.org/10.1029/2004JB003488

Yuan, Z., Li, T., Su, P., Sun, H., Ha, G., Guo, P., et al. (2022). Large surface-rupture gaps and low surface fault slip of the 2021 M\textsubscript{s} 7.4 Maduo earthquake along a low-activity strike-slip fault, Tibetan Plateau. *Geophysical Research Letter*, e2021GL096874. https://doi.org/10.5281/zenodo.5915150

Zhan, Y., Liang, M., Sun, X., Huang, F., Zhao, L., Gong, Y., et al. (2021). Deep structure and seismogenic pattern of the 2021.5. 22 Madoi (Qinghai) M\textsubscript{s} 7.4 earthquake. *Chinese Journal of Geophysics*, 64(7), 2232–2252.

Zhang, P., Deng, Q., Zhang, Z., & Li, H. (2013). Active faults, earthquake hazards and associated geodynamic processes in continental China (in Chinese). *Scientia Sinica Terra*, 43, 1607–1620. https://doi.org/10.1360/052012-405

Zhao, D., Qu, C., Chen, H., Shan, X., Gong, W., & Liu, L. (2021). Tectonic and geomorphic control on fault kinematics of the 2021 M\textsubscript{s} 7.3 Maduo (China) earthquake inferred from interseismic, coseismic, and postseismic InSAR observations. *Geophysical Research Letters*, 48, e2021GL095417. https://doi.org/10.1029/2021gl095417