The 2020 Mw6.0 Jiashi earthquake: Coinvolvement of thin-skinned thrusting and basement-shortening in shaping the Keping-tage nappe

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Abstract

The Keping-tage fold-thrust belt in southwest Tian Shan is seismically active, yet most well-recorded earthquakes occurred south of the mountain front, hindering our understanding of the orogenic process to the north. The 2020 Mw6.0 Jiashi earthquake is an important event with surface deformation in the nappe structure well illuminated by InSAR. Here, we employ the surface deformation and relocated aftershocks to investigate the fault slip distribution associated to this event. Further added by an analysis of Coulomb stress changes, we derive a fault model involving slips on a shallow low-angle (~10º) north-dipping thrust fault as well as on a left-lateral tear fault and a high-angle south-dipping reverse fault in mid crust. Our results reflect the basement-involved shorterning activated by a thin-skinned thrust faulting event with the surface deformation implying the basin-ward orogenic process of the southwest Tian Shan.

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Key Points:

- The shallow north-dipping low-angle thrust faulting dominated the rupture of the 2020 Mw6.0 Jiashi earthquake.
- A left-lateral tear fault and a south-dipping basement fault involved in the event.
- The surface deformation implies the basin-ward orogeny of the southwest Tian Shan.

Abstract

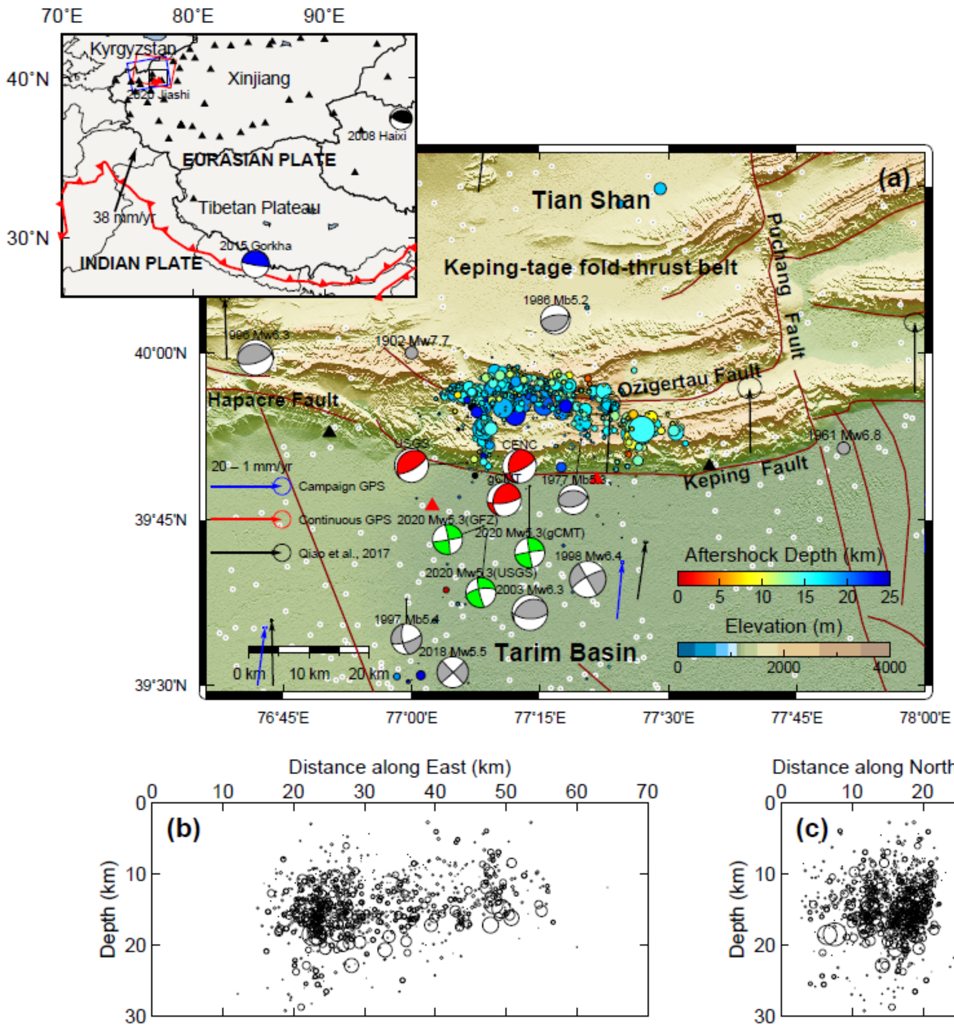
The Keping-tage fold-thrust belt in southwest Tian Shan is seismically active, yet most well-recorded earthquakes occurred south of the mountain front, hindering our understanding of the orogenic process to the north. The 2020 Mw6.0 Jiashi earthquake is an important event with surface deformation in the nappe structure well illuminated by InSAR. Here, we employ the surface deformation and relocated aftershocks to investigate the fault slip distribution associated to this event. Further added by an analysis of Coulomb stress changes, we derive a fault model involving slips on a shallow low-angle (~10^{o}) north-dipping thrust fault as well as on a left-lateral tear fault and a high-angle south-dipping reverse fault in mid crust. Our results reflect the basement-involved shortening activated by a thin-skinned thrust faulting event with the surface deformation implying the basin-ward orogenic process of the southwest Tian Shan.

Plain Language Summary

Interferometric Synthetic Aperture Radar (InSAR) is an effective technique to image the surface deformation caused by earthquakes and can be a powerful tool for studying earthquake mechanism. Aftershock distribution can help delineate faults at depth and analyze regional earthquake risk. The 2020 Mw6.0 Jiashi earthquake raises concerns for seismic risk in the southwest Tian Shan seismic belt and provides a rare opportunity to illuminate the deformation and development of the southwest Tian Shan. Here, we combine InSAR deformation measurements and relocated aftershocks to investigate the faults responsible for this earthquake. Tests of different fault models show that the combination of a shallow thrust fault and two deeper faults can best explain the surface deformation and aftershock distribution. Stress analysis suggests that slips on the shallow fault reactivated the older basement structure at depth. Our results indicate that this earthquake uplifted the southmost mountain front with relatively low topography and therefore indicates the basin-ward propagation of the southwest Tian Shan.

1 Introduction

The Tian Shan region accommodates part of the ongoing Indo-Eurasian collision since ~20-25 Ma (Tapponnier et al., 1977; Avouac et al., 1993; Abdrakhmatov et al., 1996; Yang et al., 2008). As an intra-continental orogenic belt located 1000-2000 km north of the main Himalaya collision zone, the deformation is distributed along the broadly NE-SW trending Tian Shan (Yin et al., 1998; Allen et al., 1999). Along the southern Chinese Tian Shan, multiple fold-thrust fault zones were formed due to the late Paleozoic continent-continent collision with the Tarim Basin (Yin et al., 1998; Scharer et al., 2004), in which the westernmost Kashi-Akesu thrust segment hosts the Keping-tage fold-thrust belt (Figure 1a; Yin et al., 1998; Li et al., 2020). The Keping Fault has developed in the frontier of the belt, dipping generally to the north and are upwardly steep, forming a listric structure with ramp and flat segments soling into a main basal décollement at a depth of ~10 km (e.g., Scharer et al., 2004; Tian et al., 2006; Song et al., 2006; Gao et al., 2013; Zhang et al., 2019). Being in the triple junction of the Pamir syntaxis, the South Tian Shan and the Tarim Basin (Allen et al., 1999), earthquakes with diverse mechanisms occur intensively in the Keping-tage fold-thrust belt, especially in the past 20 years or so (Figure 1a, gray beachballs). However, most of the events are located south of the belt, and no large earthquake beneath the nappe structure has been studied with modern geodetic observations, hindering the understanding on the role of earthquakes in forming the arcuate emergent imbricate structures in this region.



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72 **Figure 1**. Tectonic settings and aftershock distribution of the January 19, 2020 Mw6.0 Jiashi earthquake. (a) Dark red lines depict active faults in this region. Arrows show the GPS horizontal velocities with respect to the Eurasian Plate (blue and red, Zhao et al., 2015; black, Qiao et al., 2017). Red beachballs display focal mechanisms of the Mw6.0 Jiashi earthquake from USGS, gCMT and CENC. Green beachballs depict focal mechanisms of the Mw5.3 event (2 days before the Mw6.0 event) from gCMT, USGS and GFZ. Gray dots denote background seismicity from the USGS catalog. Gray dots and beachballs show locations and/or focal mechanisms of recorded historical events in the Keping-tage zone, including the 1902 Mw7.7 Atushi earthquake (location only, Zhang et al., 1999; He et al., 2001), the 1961 Mw6.8 Bachu earthquake (location only), the 1977 Mb5.3 Xekar earthquake (Fan et al., 1994), the 1996 Mw6.3 Atushi earthquake, the 1986 Mb5.2 southern Xinjiang earthquake (Ekström and England, 1989), the Jiashi strong earthquake swarm in 1997-1998 (Zhou et al., 2001; Xu et al., 2005), the 2013 Mw6.3 Bachu-Jiashi earthquake (Wang et al., 2005), and the 2018 Mw5.5 Jiashi earthquake (Song et al., 2019). Black and red triangles represent permanent seismic stations and portable instruments deployed by the Xinjiang Earthquake Administration after the event. Aftershocks (up to February 22, 2020) are shown as circles color-coded by focal depths and size-scaled to

magnitudes. The topleft inset shows the location of the study area. Black triangles are seismic stations used in the aftershock relocation. Blue and red rectangles indicate the coverage of SAR data. Beachballs represent the two shallow-dipping thrust earthquakes discussed in this study. (b) and (c) show projections of all relocated aftershocks onto east-west and north-south vertical planes, respectively, with the size of circles proportional to the magnitude.

On January 19, 2020, an Mw6.0 earthquake occurred in the Keping fold-thrust belt, striking Jiashi County in southern Xinjiang, China. The United States Geological Survey (USGS), global CMT (gCMT) and China Earthquake Networks Center (CENC) all located the event at the south edge of the thrust zone, and reported predominately thrust slips occurring on either a low-angle plane dipping north or a high-angle plane dipping south, both trending in the EW direction (Figure 1a; Table S1). Preliminary slip inversions using InSAR observations prefer the shallow north-dipping plane with mainly thrust slips and slight strike-slip components (Yu et al., 2020; Yao et al., 2020). However, the discrepancies between the InSAR and seismology derived dip angles and focal depths are quite large (Table S1). Focal mechanisms from gCMT and USGS W-phase inversion show a large non-double-couple component (both are ~27%), indicating a complex rupture process. Interestingly, on January 17, 2020, an Mw5.3 strike-slip earthquake occurred ~12 km south of the Mw6.0 event, probably ruptured a NS-trending sub-vertical fault plane with a left-lateral slip (Figure 1a, green beachballs). These early studies suggest that the fault geometry and rupture process of the 2020 Jiashi earthquake may be more complex than those revealed by individual type of data.

Because of the moderate size of the Jiashi event, teleseismic records may have sparse coverage and limited signal-to-noise ratios to resolve the rupture process (e.g., Institute of Tibetan Plateau Research, Chinese Academy of Sciences, http://www.itpcas.ac.cn/kycg/yjcg/202001/t20200122_5494135.html). InSAR observations can provide high-resolution, near-field constraints to quantify the fault geometry and spatial slip distribution, yet it may lack the ability to resolve the fault configuration at depth. After the earthquake, the Xinjiang Earthquake Administration deployed 2 portable seismic instruments (red triangles in Figure 1a) to augment the seismic network. Together with the 11 existing seismic stations within 150 km of the epicenter (Figure 1), ~1900 aftershocks were recorded by February 21, 2020, with significantly greater depths than the InSAR derived fault plane (Yu et al., 2020; Yao et al., 2020), suggesting the possible reactivation of basement faults.

Here, we combine InSAR observations and relocated aftershocks to image the seismogenic structure of the 2020 Mw6.0 Jiashi event. We first obtain the surface deformation from Sentinel-1 interferograms to determine the fault geometry and slip distribution on the main rupture area. We then search for the optimal combination of faults with different dipping angles and depths by fitting both the surface deformation and aftershock distribution. Combining the InSAR and seismology results with an analysis of Coulomb stress changes, we propose a conceptual fault model involving a shallow north-dipping thrust fault, a strike-slip tear fault and a south-dipping high-angle basement fault to explain the paradox between InSAR derived fault plane and aftershock distribution. Our results reveal the complexity of this event and shed lights on its role in the orogeny of southwest Tian Shan.

2 Methods

2.1 Aftershock relocation

The ~1900 aftershocks recorded by the regional seismic network from January 19 to February 21, 2020 were relocated using the double-difference algorithm (Waldhauser and Ellsworth, 2000) with the 1-D P-wave velocity model from the CRUST1.0 model (Laske et al., 2013). After the relocation procedure, we obtained locations of 1506 aftershocks with magnitudes of $-1.6 \leq M \leq 5.2$. We used 976 aftershocks with $M \geq 0$ to illuminate the fault geometry at depth (Figure 1).

2.2 InSAR data processing

We collected Sentinel-1 SAR images spanning the earthquake from ascending (AT129) and descending (DT34) tracks (Table S2). The interferograms were obtained using the Sentinel-1 Interferometry Processor (Jiang et al., 2017) and unwrapped by SNAPHU software (Chen and Zebker, 2001). The unwrapped interferograms were down sampled using the quadtree method (Jonsson, 2002), resulting in 614 and 498 data points for ascending and descending tracks, respectively (Figure S1).

2.3 Inversion of fault geometry and slip distribution

We adopted a two-step procedure to obtain the optimal fault geometry and slip distribution (e.g., Jonsson, 2002). The InSAR measurements were used to estimate the optimal fault parameters using the Geodetic Bayesian Inversion Software (GBIS; Bagnardi and Hooper, 2018). Then, we extended the fault plane in the dip and strike directions to invert for the corresponding slip distributions using the steepest descent method (Wang et al., 2009). In order to evaluate the data fitness, a dimensionless misfit is calculated using the weighted residual sum of squares (WRSS), considering the data covariance matrix (Xue et al., 2010).

2.4 Coulomb failure stress change

To investigate the potential relationship between the shallow north-dipping fault and aftershocks as well as the seismic risk on the adjacent faults, we calculated the change of Coulomb failure stress (ΔCFS) utilizing the Coulomb 3.3 software (Toda et al., 2011) with an effective friction coefficient of 0.4 and a shear modulus of 30 GPa. In using our fault models, we ignored the segments with slips less than 0.1 m and calculated ΔCFS on the derived fault planes, the high-angle segment of the Keping Fault and the Puchang Fault east of the epicenter.

3 Results

3.1 Aftershock distribution

The relocated aftershocks exhibit two distinct clusters in a generally T-shaped zone (Figure 1a). One is mainly distributed along the Ozigertau fold with a nearly EW extension of ~40 km, the other is geometrically conjugate to the first one and concentrated in a narrow zone, extending ~20 km northward from the Keping Fault to the Ozigertau Fault (Figure 1a). The depths of these aftershocks are mainly 10-25 km in the mid crust (Figures 1b and 1c). According to previous studies, the depth of the detachment fault below the Keping Fault is ~10 km (e.g., Scharer et al., 2004). The aftershocks thus likely occurred on structures beneath the detachment fault.

The first cluster can be fitted by an EW-striking, south-dipping plane with a high dip angle of 84°; whereas aftershocks in the western cluster can be fitted by a sub-vertical NS-striking fault plane, similar to one of the nodal planes of the Mw5.3 earthquake that occurred two days before the Mw6.0 event (Figure 1a, green beachballs). From their spacial distribution, the two fault planes may intersect at depth. Note that aftershocks and after-slips occurred on these two fault planes may also contribute to InSAR measurements, as the SAR images were acquired 9 (ascending) and 3 (descending) days after the main event.

3.2 InSAR derived deformation field

The interferograms (Figures 2a and 2b) exhibit a clear deformation pattern that shows two elliptical areas elongated in the EW direction with clear fringes spreading ~50 km. The deformation patterns from ascending and descending orbits are similar, suggesting that the line-of-sight (LOS) displacements mainly reflect the vertical motion. The earthquake caused ~5 cm of subsidence on the northern Ozigertau fold lobe, and ~7 cm of uplift between the EW-striking Keping and Ozigertau faults, implying that this event mainly ruptured a gently-dipping fault between these two faults (Figures 2c and 2d). The subsidence area coincides with the EW-trending aftershock cluster. No phase discontinuity is observed from both interferograms, indicating that the rupture did not reach the surface. Deformation and topography profiles along the NS direction display an obvious ‘bell-shaped’ pattern. Uplift occurred in the area of relatively low elevation, while subsidence occurred in the area of relatively high elevation (Figures 2e and 2f).

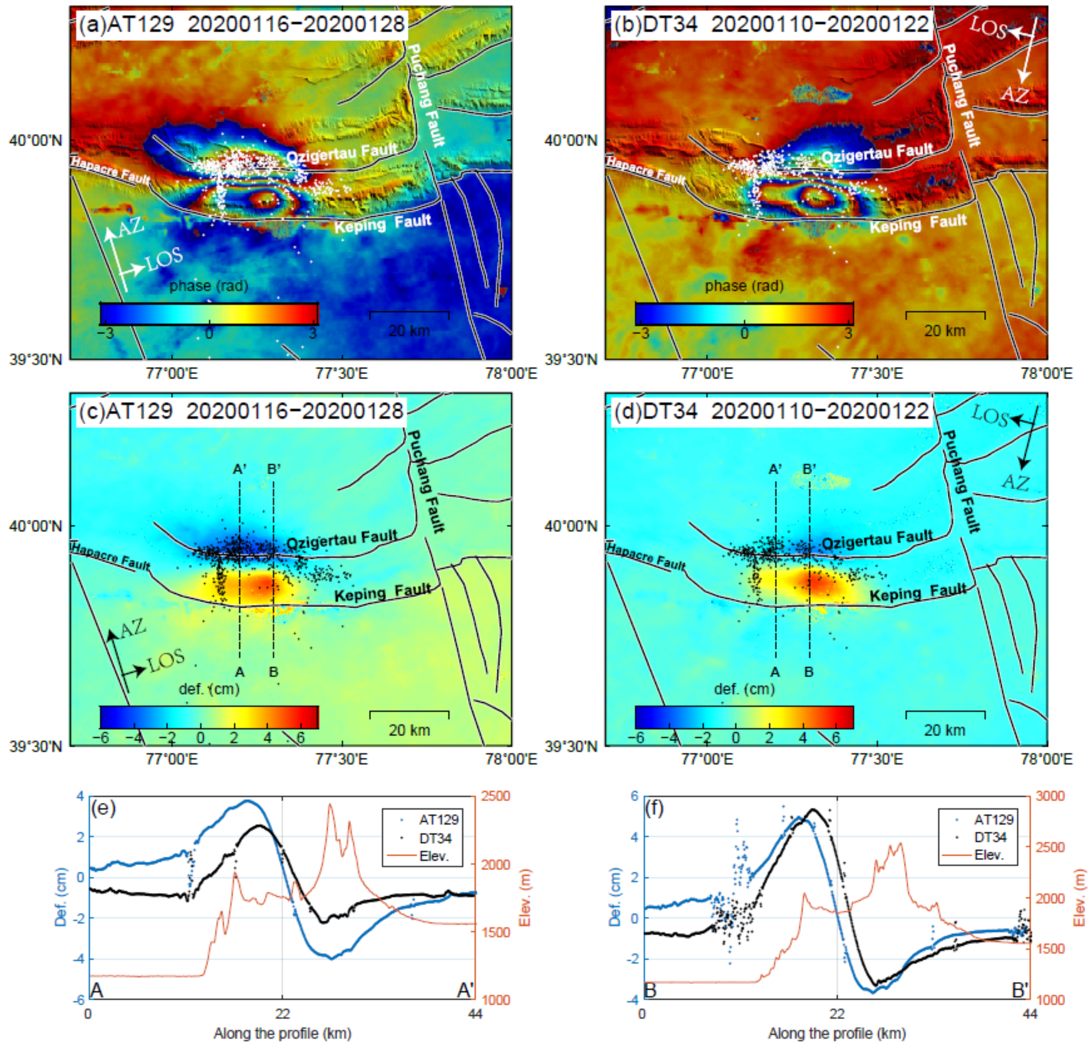

Figure 2. Surface deformation associated with the 2020 Mw6.0 Jiashi earthquake from Sentinel-1 SAR interferograms. (a) and (b) show interferograms from ascending (AT129) and descending (DT34) tracks, respectively. Each fringe represents 2.8 cm of line-of-sight deformation. White dots show relocated aftershocks during the SAR acquisition time. (c) and (d) show the corresponding deformation with black dots representing aftershock distributions. (e) and (f) display the deformations (DT34 in blue and AT129 in black) along the NS profiles AA' and BB', respectively, with the elevation shown in orange.

3.3 Single fault geometry and slip distribution

Due to the fault plane ambiguity in focal mechanisms, reverse slips on either a high-angle, south-dipping fault or on a low-angle north-dipping fault can cause similar surface deformation patterns for the main event. We therefore set both nodal planes as initial fault in our geodetic inversion (Models 1 and 2 in Table S3). Results show that the surface deformation can be better fitted by a 10.2° ± 7.4° north-dipping fault with a depth of 6.9 ± 1 km (Model 1). The detailed inversion results and data fitness are provided in Figures S2-S9 and Tables S3-S5. Our preferred model has a smaller dip angle (10.2º) than the 20º in the model presented in Yao et al. (2020), but is generally consistent with the 9º from the USGS body-wave mechanism and the 8.8º in Yu et al. (2020) (Table S1).

The slip distribution in our preferred model displays predominantly thrust motion with a slight left-lateral strike-slip component (Figures 3 and S6). The slips are mainly distributed in a depth range of ~6-8.5 km, and probably arrested by the detachment fault at ~10 km depth. Assuming a Poisson's ratio of 0.25 and a shear modulus of 30 GPa, the geodetic moment is ~1.332×10^{18} N·m, i.e., Mw6.08, which is slightly larger than that obtained from USGS and gCMT (Mw6.0).

3.4 Coulomb stress change

To analyze the possible triggering effect between the shallow north-dipping fault and deep aftershocks, we calculated the Coulomb stress changes caused by our preferred single-fault model to the deep south-dipping and strike-slip faults inferred from aftershock distribution. Due to the lack of focal mechanisms of aftershocks, we set strike-slip (left- and right-lateral) mechanisms on sub-vertical NS-trending faults, as well as strike-slip, reverse and normal mechanisms on faults dipping 84° to the south as receiving faults (Figures 4d-4l and S10). Results show that aftershocks of the western cluster mainly fall in the area with increased Coulomb stress when a left-lateral strike-slip fault is used as the receiving fault (zone ‘A’, Figures 4d-4f). The nearly EW-distributed aftershocks are well located in the loading area of the Coulomb stress when the south-dipping fault is set as a reverse fault (zone ‘B’, Figures 4g-4i). The Coulomb stress changes exceed the triggering threshold of 0.1 bar (Kilb et al., 2000), implying that the shallow north-dipping fault may have a large triggering effect on the complex deep structures. Interestingly, a few aftershocks at depth of ~15 km to the east are well located in the loading area for a right-lateral strike-slip fault plane (zone ‘C’, Figures 4j-4l).

The Coulomb stress changes due to the Mw6.0 event on the adjacent mapped faults are relatively small. Even though the loading effect on the shallow high-angle segment of the Keping Fault has reached the loading threshold at ~4 km, few aftershocks occurred shallower than 5 km (Figure S11). The rupture of the low-angle thrust has a certain triggering effect on subsequent seismic activity outside the rupture area at depths of 5-9 km (Figure S12). The Coulomb stress on the middle segment of the strike-slip Puchang Fault (Figure 1a) has slightly increased at the shallow depth of 0-10 km (~0.05 bar; Figure S13).

3.5 Multi-fault geometry and slip distribution

Although our shallow north-dipping model can explain the InSAR observations reasonably well, the large none-double-couple component revealed from the seismological data and the deep aftershock distribution imply that multiple faults may be involved during the 2020 Jiashi event. We therefore designed another 4 models with multi-fault configurations (Models 3-6 in Table S3), where fault geometries of the two deep faults are inferred from relocated aftershocks with faulting mechanisms from analysis of Coulomb stress changes (Table S6). When we added the deep south-dipping and strike-slip faults delineated by aftershocks to the shallow north-dipping fault model, the data-model correlation increases from 96.92% to 97.93%, and the misfit decreased from 0.0274 to 0.0226 (Table S3, Figures 3c-3h and Figures S14-S19). The deep faults alone yield a very poor data fitness with a data-model correlation of 79.59% (Model 5 in Table S3 and Figure S19), strongly suggesting that aftershocks and main slips were distributed on different fault planes. The rupture on all three faults yields a moment magnitude of Mw6.17, which is larger than the magnitude obtained by seismic data (Mw6.0). Considering that aftershocks and after slips may cause surface deformation as well, part of the observed surface signal maybe caused by these post-seismic processes.

Although our InSAR observations do not have enough temporal resolution to distinguish coseismic and early post-seismic deformation, given the relatively large left-lateral strike-slip component in the gCMT, we propose that the NS-trending fault may have ruptured coseismically, consistent with the early Mw5.3 strike-slip event. We obtain a new moment tensor by superimposing the shallow north-dipping and the deep strike-slip faults, which is more consistent with solutions from gCMT and USGS W-phase than the one derived from a single north-dipping thrust obtained by InSAR data (Figure 3b). The seismologically determined epicenter of the Mw6.0 event is located near the southern tip of the NS-trending fault defined by relocated aftershocks, rather than the location of maximum thrust slip. Thus, the Mw6.0 event might be initiated on the strike-slip fault and then propagated to the north. We do not have sufficient evidence to conclude whether the deep south-dipping fault ruptured coseismically. Further studies on joint inversion may yield more detailed image of the dynamic rupture process.

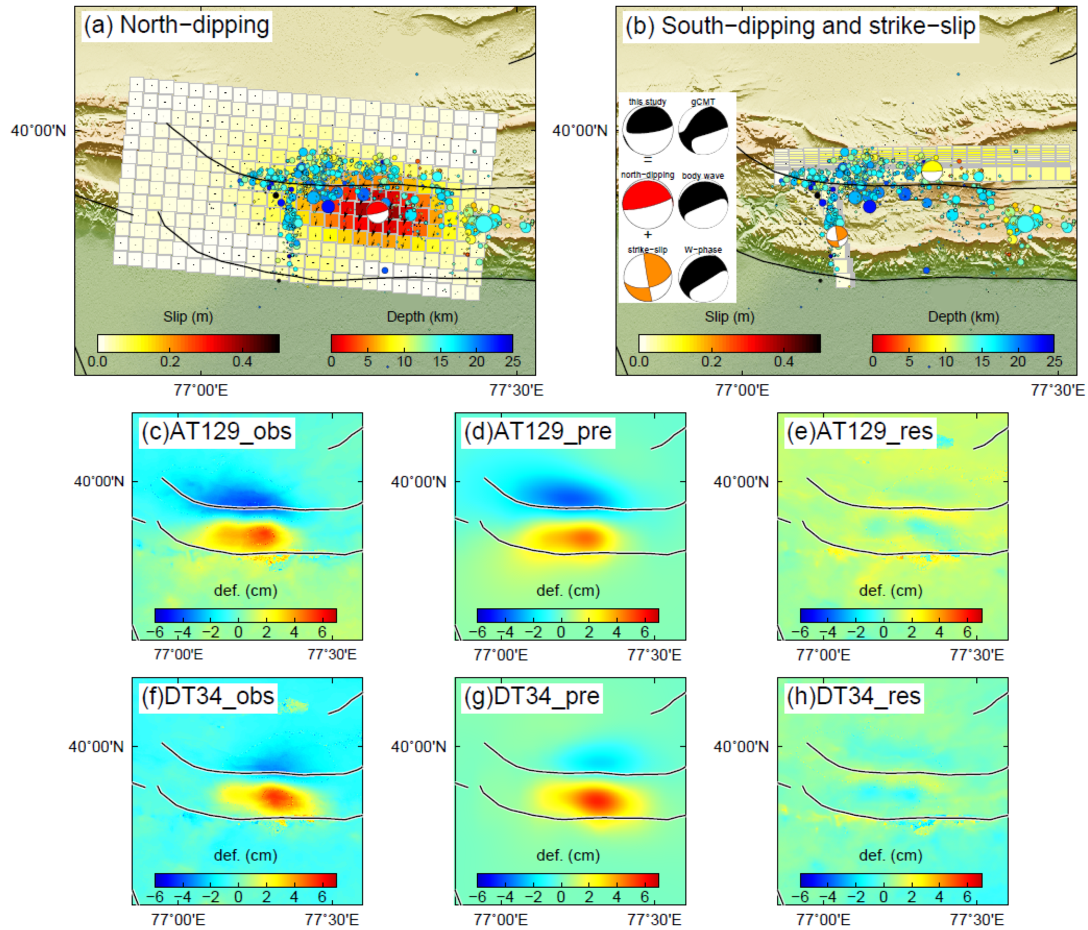

Figure 3. Map views of the slip distributions on (a) the shallow north-dipping fault and (b) the deep south-dipping and strike-slip faults inferred from aftershock distribution. Red, orange, and yellow beachballs depict the focal mechanism of the north-dipping thrust fault, the deep strike-slip fault and the south-dipping reverse fault, respectively. Circles represent relocated aftershocks as in Figure 1. (c-h) Observed,

predicted and the residual maps based on our preferred Model 6 in Table S3 for the ascending (top row) and the descending tracks (bottom row).

4 Discussion and conclusions

4.1 Coinvolvement of shallow thrusting and basement-shortening during the 2020 Jiashi earthquake

Moderate-sized earthquakes can have complex ruptures and complicated aftershock distributions, which have been illuminated by surface ruptures (e.g., Lo et al., 2019) and/or regional and near-field seismological observations (e.g., Poli et al., 2016). In contrast, the 2020 Jiashi earthquake exhibits a rather simple and smooth surface deformation, making it difficult to resolve the faulting complexity using InSAR data alone. Yu et al. (2020) propose that the area below the main rupture is stress-enhancing. Our Coulomb stress analysis is consistent with their conclusion yet with more details, thanks to the relocated aftershocks (Figures 4d-4l).

Our modeling reveals a high-angle south-dipping structure located well beneath the detachment fault. Plenty of basement faults have been identified in the Tarim Basin, cutting through both the basement or the sedimentary covers, and mainly located at the margin of the basin, where both normal and thrust faults have developed (Lin et al., 2015). The marginal basement faults are mainly thrust faults with basin-ward inclination, and their directions are consistent with the basin's boundaries. As the Tian Shan overthrust the Tarim Basin since ~20-25 Ma (e.g., Tapponnier et al., 1977; Avouac et al., 1993; Li et al., 2020), the detected deep south-dipping reverse fault may be an old structure belonging to the Tarim block. Triggered by the shallow slips during the 2020 Jiashi earthquake, the basement fault might be reactivated, leading to aftershocks. The inferred south-dipping basement fault also suggests the development of basement shortening during a shallow, thin-skinned thrust event with moderate size (e.g., Lacombe and Mouthereau, 2002).

Different shortening rates have been observed among different segments of the Keping-tage nappe throughout the Cenozoic period (Li et al., 2020). Therefore, along its southern margin, the nearly NS-trending strike-slip faults play important roles in regulating the along-strike variation of collision rates, e.g., the Puchang Fault (Figure 1a; Yin et al., 1998; He et al., 2002; Zhang et al., 2019; Li et al., 2020). Several strike-slip earthquakes occurred south of the Keping-tage fold-thrust zone (Figure 1a). Similar to these strike-slip faults, the blind left-lateral strike-slip fault delineated by the 2020 Mw5.3 earthquake and the nearly NS-trending aftershocks may also be the consequence of different shortening rates. Aftershocks to the east of the main rupture area might also indicate a right-lateral strike-slip blind fault (Figures 4a-4b and 4j-4l). Together with the left-lateral fault to the west, they exhibit a block of box-like extrusion bounded by two tear faults (Figures 4a and 4b). We infer that the strike-slip tear faults at depth may extend to the south of the fold-thrust zone, adjusting the variation of shortening rates in this region.

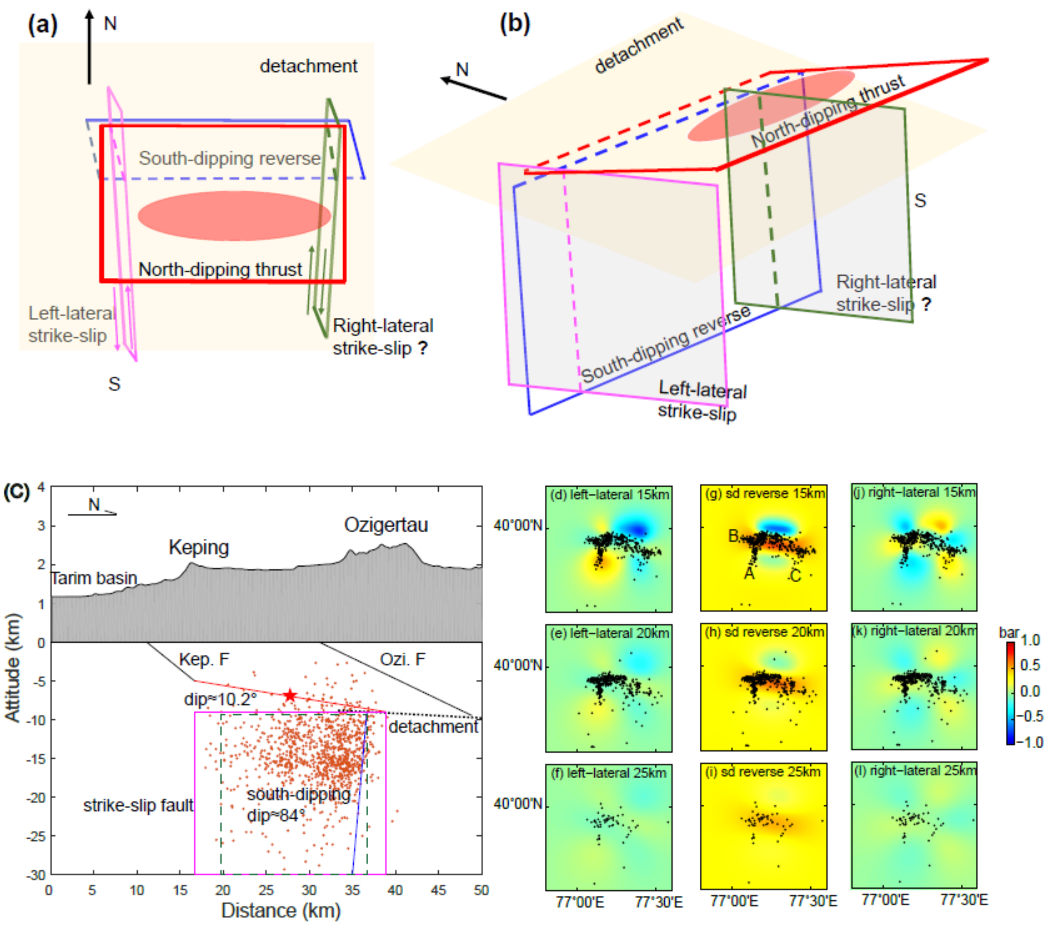

Figure 4. Seismogenic faults during the 2020 Jiashi earthquake. (a) and (b) shows top and side views of the conceptual model. (c) NS projection of faults and all relocated aftershocks. Red star represents the centroid of the slip distribution on the shallow

north-dipping Keping thrust segment (red box). The magenta and dark green boxes are side views of the deep left-lateral and right-lateral strike-slip faults, respectively, and the blue line represents the deep south-dipping reverse fault delineated by aftershocks. Kep.F: Keping Fault; Ozi.F: Ozigertau Fault. (d-l) Changes of Coulomb stress at depths of 15 km, 20 km and 25 km due to the rupture of shallow north-dipping thrust on the deep left-lateral fault to the west (d-f), the deep south-dipping reverse fault beneath the main rupture area (g-i), and the deep right-lateral fault to the east (j-l). Black dots show epicenters of aftershocks at corresponding depths. A, B and C represent the three main aftershocks distribution zones.

Note that due to the sparse near-field seismic stations and the large topographical fluctuations in this region, aftershock relocation based on simple 1-D velocity model may have larger uncertainty in hypocentral depth. Focal mechanisms of aftershocks and detailed geological investigations are required to further interpret structures beneath the detachment fault.

4.2 Basin-ward orogenic process revealed by the surface deformation

The 2020 Mw6.0 Jiashi event is the first earthquake occurred beneath the Keping fold-thrust belt to be well imaged by geodetic data, providing a rare opportunity to study the role of earthquakes in shaping the topography in a nappe tectonic setting. This event lowered the high mountain along the Ozigertau Fault, whereas uplifted the relatively lower mountain front along the youngest Keping thrust, likely implying propagation of the orogenic deformation into the basin. This type of surface deformation has also been observed in other intracontinental low-angle thrust events, such as the 2008 Mw6.3 Haixi, Qinghai earthquake (Daout et al., 2019) and the 2015 Mw7.8 Gorkha, Nepal earthquake (Elliott et al., 2016) (Table S6 and beachballs in Figure 1 inset). Due to the flattern effect of this event, we suspect that the long-term aseismic process or plastic folding contribute positively to the local topography in this region.

We conclude that the January 2020 Mw6.0 Jiashi earthquake involves ruptures of a multi-fault system in both shallow and mid crust. The deformation pattern reveals the basin-ward propagation of orogenic deformation in shaping the nappe structure during the low-angle thrust faulting. Further analyses are necessary to apply InSAR observations to resolve the deformation in the post- and inter-seismic stages and quantify the contributions of elastic and plastic deformation during the orogenic process in southwest Tian Shan.

Acknowledgments

Figures are generated by the Generic Mapping Tools 5.4.3 (Wessel et al., 2013). Sentinel-1 SAR imges are copyrighted by the European Space Agency and processed by the Sentinel-1 Interferometry Processor software (Jiang et al., 2017) (available at http://sarimggeodesy.github.io/software). We are grateful for insightful discussions with Heng Luo from Wuhan University and Xuhua Shi from Zhejiang University. This work has been supported by the National Science Foundation of China (Grants 42021003, U1939202, 41974017 and 41774067). The data and model in this study can be accessed at https://disk.pku.edu.cn:443/link/E1479A04ADBC76C0A1C077C37B061B2C

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